Calhoun
Institutional Archive of the Naval Postgraduate School

Calhoun: The NPS Institutional Archive

DSpace Repository

Theses and Dissertations | 1. Thesis and Dissertation Collection, all items

1991-09

Multiple-wavelength transmission measurements in rocket motor plumes.

Kim, Hong-on

Monterey, California. Naval Postgraduate School

http://hdl.handle.net/10945/26645

Downloaded from NPS Archive: Calhoun

http://www.nps.edu/library

Calhoun is the Naval Postgraduate School's public access digital repository for research materials and institutional publications created by the NPS community. Calhoun is named for Professor of Mathematics Guy K. Calhoun, NPS's first appointed -- and published -- scholarly author.

Dudley Knox Library / Naval Postgraduate School
411 Dyer Road / 1 University Circle
Monterey, California USA 93943

NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA 93943-5002

NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

MULTIPLE-WAVELENGTH
TRANSMISSION MEASUREMENTS
IN ROCKET MOTOR PLUMES

by

Hong-on Kim

September, 1991

Thesis Advisor: David W. Netzer
Co-Advisor: David Laredo

Approved for public release; distribution is unlimited

T257825

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION Unclassified	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.
2b DECLASSIFICATION/DOWNGRADING SCHEDULE	
4 PERFORMING ORGANIZATION REPORT NUMBER(S)	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a NAME OF PERFORMING ORGANIZATION Naval Postgraduate School 6b OFFICE SYMBOL (*If applicable*) 55	7a NAME OF MONITORING ORGANIZATION Naval Postgraduate School
6c ADDRESS (*City, State, and ZIP Code*) Monterey, CA 93943-5000	7b ADDRESS (*City, State, and ZIP Code*) Monterey, CA 93943-5000
8a NAME OF FUNDING/SPONSORING ORGANIZATION Air Force Phillips Laboratory 8b OFFICE SYMBOL (*If applicable*)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c ADDRESS (*City, State, and ZIP Code*) Edwards AFB, CA 93523-5000	10 SOURCE OF FUNDING NUMBERS Program Element No / Project No / Task No F0461191X004 / Work Unit Accession Number

11 TITLE (*Include Security Classification*)
MULTIPLE-WAVELENGTH TRANSMISSION MEASUREMENTS IN ROCKET MOTOR PLUMES

12 PERSONAL AUTHOR(S) Kim, Hong-on

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (*year, month, day*)	15 PAGE COUNT
Master's Thesis	From To	1991, September	63

16 SUPPLEMENTARY NOTATION
The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

17 COSATI CODES			18 SUBJECT TERMS (*continue on reverse if necessary and identify by block number*)
FIELD	GROUP	SUBGROUP	Solid -Propellant; Rocket Motor; Light Transmission; Particle Sizing

19 ABSTRACT (*continue on reverse if necessary and identify by block number*)

Multiple-wavelength light transmission measurements were used to measure the mean particle size (d32), index of refraction (m) and standard deviation of the small particles in the edge of the plume of a small solid propellant rocket motor. The results have shown that the multiple-wavelength light transmission measurement technique can be used to obtain these variables. The technique was shown to be more sensitive to changes in d32 and standard deviation than to m. A GAP/AP/4.7 % aluminum propellant burned at 25 atm produced particles with d32 = 0.150 +/- 0.006 microns, standard deviation = 1.50 +/- 0.04 and m = 1.63 +/- 0.13. The good correlation of the data indicated that only submicron particles were present in the edge of the plume.

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT	21 ABSTRACT SECURITY CLASSIFICATION	
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS REPORT ☐ DTIC USERS	Unclassified	
22a NAME OF RESPONSIBLE INDIVIDUAL Prof. David W. Netzer	22b TELEPHONE (*Include Area code*) (408) 646-2980	22c OFFICE SYMBOL Code AA/Nt

DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted
All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE

Approved for public release; distribution is unlimited.

Multiple-Wavelength Transmission Measurements
in Rocket Motor Plumes

by

Kim, Hong-on
Major, Korean Air Force
B.S., Korean Air Force Academy

Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
September, 1991

ABSTRACT

Multiple-wavelength light transmission measurements were used to measure the mean particle size (d_{32}), index of refraction (m) and standard deviation (σ) of the small particles in the edge of the plume of a small solid propellant rocket motor. The results have shown that the multiple-wavelength light transmission measurement technique can be used to obtain these variables. The technique was shown to be more sensitive to changes in d_{32} and standard deviation (σ) than to m. A GAP/AP/4.7 % aluminum propellant burned at 25 atm produced particles with $d_{32} = 0.150 \pm 0.006\ \mu$, $\sigma = 1.50 \pm 0.04$ and $m = 1.63 \pm 0.13$. The good correlation of the data indicated that only submicron particles were present in the edge of the plume.

11 0313
4/14/57
c.1

TABLE OF CONTENTS

I. INTRODUCTION 1

II. THEORETICAL BACKGROUND 4

III. EXPERIMENTAL APPARATUS 7

A. ROCKET MOTOR 7

B. LIGHT TRANSMITTANCE APPARATUS 9

C. DATA ACQUISITION AND REDUCTION 11

IV. RESULTS AND DISCUSSION 17

A. INTRODUCTION 17

B. SYSTEM CALIBRATION 18

C. ROCKET MOTOR PLUME DATA 18

V. CONCLUSIONS AND RECOMMENDATIONS 40

APPENDICES 41

A. DIODE READINGS 41

B. DATA ACQUISITION PROGRAM 47

REFERENCES 50

INITIAL DISTRIBUTION LIST 52

LIST OF FIGURES

III-1. Photograph of the Motor Components 13

III-2. Photograph of Installed Rocket Motor 13

III-3. Photograph of Light Transmittance System 14

III-4. Schematic Diagram of Light Transmittance Apparatus 15

III-5. Spectral Irradiance of the Hg Lamp 16

III-6. Diode Spectral Response 16

IV-1. Configurations of the Motor and Plume 19

IV-2. Voltage vs. Diode Number Run 1 without Plume 26

IV-3. Voltage vs. Diode Number, Run 1, in Plume 27

IV-4. Voltage vs. Diode Number, Run 2, without Plume 28

IV-5. Voltage vs. Diode Number, Run 2, in Plume 29

IV-6. Voltage vs. Diode Number, Run 3, without Plume 30

IV-7. Voltage vs. Diode Number, Run 3, in Plume 31

IV-8. Extinction Coefficients 32

IV-9. Extinction Coefficient Ratios 33

IV-10. Iteration Flow Scheme 34

IV-11. Data Correlation Sensitivity for Specified D_{32}, Run 1 35

IV-12. Data Correlation Sensitivity for Specified σ, Run 1 36

IV-13. Data Correlation Sensitivity for Specified m, Run 1 37

IV-14. Log Transmission vs. Extinction Coefficient Ratios, Run 1,2 & 3 38

IV-15. Log Transmission vs. Extinction Coefficient Ratios, Including 0.6328 μ Laser Data, Run 3 39

LIST OF TABLES

III-1. NOZZLE SPECIFICATIONS 8

III-2. LIGHT SPECIFICATIONS 9

III-3. MULTISPEC SPECIFICATIONS 10

IV-1. SUMMARY OF MOTOR FIRINGS 19

IV-2. DIODE READINGS AND TRANSMITTANCE 21

IV-3. LOG TRANSMISSION RATIOS 21

IV-4. REGRESSION ANALYSIS FOR THE RUNS 23

IV-5. ESTIMATES OF MEASUREMENT ACCURACY, RUN 2 25

ACKNOWLEDGEMENTS

I would like to offer my most sincere thanks and appreciation to Prof. David W. Netzer for giving me the apportunity to work with him on this project. There are no words to describe his support and guidance during the research period. I'm similarly grateful to Dr. David Laredo whose expertise in this area was invaluabe. I would also like to thank the Aeronautical Engineering technical staff for their assistance in making the necessary apparatus.

Finally, Thanks to my wife, Myoung-sook, and my lovely daughter, Jee-youn, for their support and understanding.

I. INTRODUCTION

In today's budget concious industry, the solid propellant rocket motor is an ideal propulsion system due to its low cost and simplicity. The major obstacle for solid rocket motors, however, is their limited specific impulse compared to airbreathing motors. One way to help overcome this limitation is to utilize metal fuel additives. Solid propellant rocket motors can achieve high specific impulse with metal fuel additives such as aluminum. Aluminum propellants also increase propellant densities and suppress transverse modes of combustion oscillations by damping the oscillations with the aluminum agglomerates in the combustion chamber. One disadvantage of using metal fuel additives that cause large agglomerates in a rocket motor is a large thrust loss. The agglomerates remain as relatively large condensed particles in the nozzle expansion process, resulting in velocity and thermal lags between the condensed particles and the expanding gas. Additional losses occur due to the fact that, unlike a gas, the condensed particles do not expand in the nozzle expansion area. These losses, called two phase flow losses, are often the largest factor in the determination of the nozzle loss coefficient [Ref. 1]. Besides causing performance losses in the nozzle, the condensed Al_2O_3 particles are the major source of primary smoke in the exhaust plume. This has significance when missiles are designed for tactical purposes and plume signature is a critical issue. The particulate matter can also have major effects upon the plume IR signature. High number densities of particles can block gas-phase radiation from the plume. They can also be the

source of radiation, especially the larger particles which exit the nozzle not in thermal equilibrium with the gas. The detection, identification, tracking and targeting of missiles that employ these propellants are all important issues in the development of space defence systems.

The prediction of plume signature is currently accomplished using codes such as SPF and SIRRM [Ref. 2]. The nozzle/plume flowfield codes [Ref. 2, 3] predict that the particle size distribution within the plume is not uniformly distributed in the radial direction. Particles larger than approximately 3μ are concentrated along the plume centerline, failing to follow the rapid gas flow turning that occurs in the nozzle throat region. Even particles as small as 1μ are predicted not to follow the flow along the diverging nozzle wall. Thus, it is expected that particles in the outer regions of the plume will be less than 1μ in diameter.

The particle size distribution, particle composition and particle optical properties all have considerable influence on the plume signature. Both the prediction of plume signature and the measurement of particle size distributions within the plume depend upon an accurate knowledge of the particle optical properties, especially the particle complex refractive index. For aluminum oxide the refractive index is generally believed to be between 1.65 and 1.85, whereas the absorption coefficient has been reported to be between 10^{-2} and 10^{-7} [Ref. 4]. Small amounts of contaminants can apparently have a significant effect on the refractive index. This is of importance in rocket motor plumes since contaminants such as soot are present and the rapidly changing temperatures can result in various phases of aluminum oxide being present.

Larger booster motors use propellants with 14-20 % aluminum by weight, resulting in 25-38 % of the exhaust being condensed Al_2O_3. These plumes are very opaque, making optically based particle sizing diagnostic techniques difficult to employ.

The objective of the present investigation was to measure the mean particle size and particle index of refraction in the plume of a small solid propellant rocket motor which utilized a propellant with 4.7 % aluminum. The technique employed was multiple-wavelength light transmission measurements together with the use of Mie code for obtaining the mean extinction coefficients as a function of the particle size distribution, index of refraction and wavelengths of the illumination source. This technique is limited to particles smaller than approximately 1.0 μ [Ref. 5]. For this reason and the high plume opacity, the measurements were made within the edges of the plume. A collimated mercury light source was used to provide five distinct wavelengths for use with a spectrograph. A helium-neon laser was also used. Measurement sensitivity to the experimental variables was also investigated.

II. THEORETICAL BACKGROUND

The light transmittance technique incorporates the use of multiple-wavelengths of light for continuous transmittance measurements through an exhaust plume containing particles. The values of transmittance are ratioed to each other and the mean particle size (d_{32}) can then be calculated from the Mie theory, which describes the complex light scattering phenomena [Ref. 6].

This procedure was successfully applied by K. L. Cashdollar to measure the mass concentration and particle size of a cloud of smoke as discussed below [Ref. 5]. The transmission of light through a cloud of uniform particles is given by Bouguer's law:

$$T=\exp(-QAnL)=\exp\left[-\frac{3QC_mL}{2\rho d}\right] \qquad (1)$$

where T = the fraction of light transmitted,

Q = the dimensionless extinction coefficient,

A = the cross sectional area of a particle,

n = the number concentration of particles,

L = the path length containing particles,

C_m = the mass concentration of particles,

ρ = the density of an individual particle, and

d = the particle diameter.

Mie scattering theory for single spherical particle can be used to calculate the extinction coefficient (Q) as a function of particle size, wavelength of light and complex refractive index of the particle. For polydisperse systems of particles, Dobbins [Ref. 7] showed that Bouguer's transmission law could be written in terms of mean properties :

$$T=\exp\left[-\frac{3\bar{Q}C_m L}{2\rho d_{32}}\right] \qquad (2)$$

where $\bar{Q}$ = mean extinction coefficient

d_{32} = the volume-to-surface mean particle diameter.

Equation (2) can be put into a more useful format by taking the natural log of both sides.

$$\ln T=\bar{Q}\left(-\frac{3C_m L}{2\rho D_{32}}\right) \qquad (3)$$

Multi-wavelength transmission measurements are made over identical path lengths through the exhaust plume. The ratios of the logarithm of the transmissions at any two wavelength is thus equal to the ratio of the calculated mean extinction coefficients for the same wavelengths [Ref. 5].

$$\left(\frac{\ln T(\lambda_i)}{\ln T(\lambda_j)}\right)_{experimental}=\left(\frac{\bar{Q}(\lambda_i, d_{32})}{\bar{Q}(\lambda_j, d_{32})}\right)_{theroetical} \qquad (4)$$

The transmittances are found experimentally. A computer program provided by K. L. Cashdollar [Ref. 5] was used to generate the mean extinction coefficients ($\bar{Q}$) and the

extinction coefficient ratios ($\bar{Q}(\lambda_1)/(\bar{Q}(\lambda_2))$ versus d_{32}. These calculations were made for various values of the complex refractive index (m) of the particle and the standard deviation (σ) of the assumed log-normal particle size distribution. If the complex refractive index and standard deviation are correct, all the ratios would yield the same particle size (d_{32}) within experimental measurement accuracy.

If the size of the submicron particles thought to be present in the edges of the plume can be assumed to obey a log-normal distribution, then there are four variables which must be determined; d_{32}, σ, and the real an imaginary parts of the index of refraction. The latter was assumed independent of λ. Calculations with the Mie code showed that $\bar{Q}$ was insensitive to the absorption index for the expected values between 10^{-2} and zero. Thus, for transmission measurements, the aluminum oxide particles were assumed to have no absorption index. This resulted in the need for a minimum of three independent log-transmission ratios to determine d_{32}, σ and the refractive index (m).

III. EXPERIMENTAL APPARATUS

A. ROCKET MOTOR

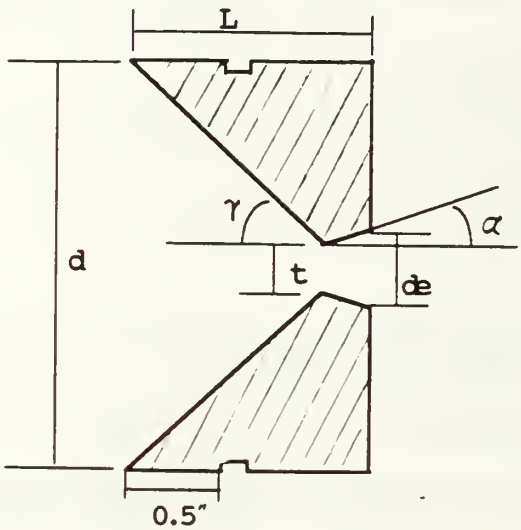
The rocket motor used in this experiment had the same internal dimensions as the long motor described by Rosa [Ref. 8]. The exterior of the motor was modified to remove the windows and make the outside diameter smaller. The motor components are displayed in a photograph in Figure III-1, and the installed motor is shown in Figure III-2.

An end-burning propellant grain was used with a 2" diameter and 1" web. The propellant was provided by the Air Force Philips Laboratory and was a GAP/AP propellant containing 4.7% aluminum. Motor ignition was accomplished using a small $BKNO_3$ igniter located near the head-end of the motor. A disposable 1000 psi burst disk was installed to reduce the potential for motor over-pressurization. A single pressure port was located in the combustion chamber. The pressure port was connected to a Teledyne 0 ~ 1000 psi pressure transducer.

The outside dimensions of the motor chamber were approximately 10.5" in length by 3.25" in diameter. During actual motor loading, propellant surfaces in contact with motor walls were coated with commercially available 732-RTV self-vulcanizing silicone rubber to provide a burning inhibitor and to maintain propellant position in the motor.

The specifications and schematic of the nozzle are shown in TABLE III-1.

TABLE III-1. NOZZLE SPECIFICATIONS



	Description	Copper Nozzle
1	Outside Diameter (d)	2.12 inches
2	Length (L)	1.24 inches
3	Throat Diameter (t)	0.200 inches
4	Exit Diameter (d_e)	0.381 inches
5	Converging half-angle (γ)	45.0 degrees
6	Diverging half-angle (α)	15.0 degrees

B. LIGHT TRANSMITTANCE APPARATUS

The complete light scattering equipment with rocket motor in place is shown in Figure III-3. The overall arrangement of the light systems is seen in the photograph. The light sources used were a mercury lamp and a helium-neon laser. The cross pattern was used so that both light sources would penetrate the same path length in approximately the same plume location. Specifications are given in TABLEs III-2 and III-3.

The light scattering apparatus is depicted schematically in Figure III-4. The collimated white light beam was provided by a 100W Hg lamp (Oriel Model 6281). The ten distinct wavelengths produced by the mercury lamp are presented in Figure III-5 [Ref. 9]. The light transmitted through the plume entered a fixed input slit (Oriel Model 77220) which was 25 μ wide and 3 mm high, and fell upon the optics inside the Oriel

TABLE III-2. LIGHT SPECIFICATIONS

	White Light Source	He-Ne Laser
Manufacturer	Oriel	Spectra Physics
Model	6281	147
Type	Mercury Arc	He-Ne CW
Output Power	-	8 mW
Beam Diameter	-	0.92 mm
Wavelength	0.365, 0.4047, 0.4358, 0.5461, 0.577 μ	.6328 μ

TABLE III-3. MULTISPEC SPECIFICATIONS

Design	Crossed Czerny-Turner
F number	3.7
Focal length	125 mm
Grating type	Plane (Holographic)
Grating mount	Kinematic
Drive	Micrometer (Calibrated)
Optical Axis Height	1.78 in (45.2 mm)
Dimension	6×6×3 inch (150×150×80 mm)
Weight	3.3 lbs (1.5 kg)

MultiSpec spectrograph (Model 77400). MultiSpec was designed to be compatible with linear diode array detectors, and has a flat focal field for use with diode arrays up to 1 inch (25 mm) long. This instrument has a low F-number of 3.7, a focal length of 125 mm, a grating (Model 77420) with a spectral range of 250–800 nm, and a flat focal field. Gratings are selected to permit use of the wavelength band of interest. The photodiode array employed was a Reticon G-series solid state scanning device consisting of 1024 photodiodes on 25 micron centers. The response characteristics of the diode are presented in Figure III-6. With these characteristics only five wavelengths of the Hg source could be detected. The overall length of the array was one inch.

An 8 mW He-Ne was also used to penetrate the plume. The 0.6328 μ wavelength was used to provide a longer wavelength than that detectable by the Multispec system. A Newport photosensor diode was used with a narrow-pass He-Ne filter to eliminate ambient/plume light.

C. DATA ACQUISITION AND REDUCTION

Details of the data acquisition system are presented in references 8 and 11. A Hewlett Packard HP9836S computer served as the system controller for the diode array of the white light source. Data was converted from analog to digital and stored in a HP6942A multiprogrammer. The HP9836S has two internal disk drives which were used to store data after acquision. The program written by Harris [Ref. 11] was revised for this experiment and is presented in APPENDIX B. An electrically operated shutter was installed on the outlet of the white light source. Eight consecutive scans of the photodiode array in the exhaust were made with the shutter open, followed by four scans with the shutter closed to determine if significant radiation from the plume affected any wavelengths of the light source. An IBM PC AT computer was used to take data from the He-Ne laser. The point during the firing when the data was taken was also controlled by the IBM computer. This was accomplished by monitoring the motor chamber pressure and specifying a time delay after steady state operation was obtained.

The data was reduced in accordance with the revised computer program of Rosa [Ref. 8]. The multiple photodiode scans were averaged and the resultant scan was plotted

on a graph of voltage versus photodiode number. The digital data was also recorded. The experimentally obtained log-transmittance ratios were compared to the theoretically generated extinction-coefficient ratios from the Cashdollar program. The computer program provided the extinction coefficients vs. d_{32} as a function of standard deviation (σ) and refractive index (m) for each wavelength. The computations were repeated for different values of σ, refractive index (m) and d_{32} interactively at the computer terminal until the theoretical data and experimental data coincided. Estimates for the initial values of the standard deviation (σ) and the refractive of index (m) were chosen from the literature.

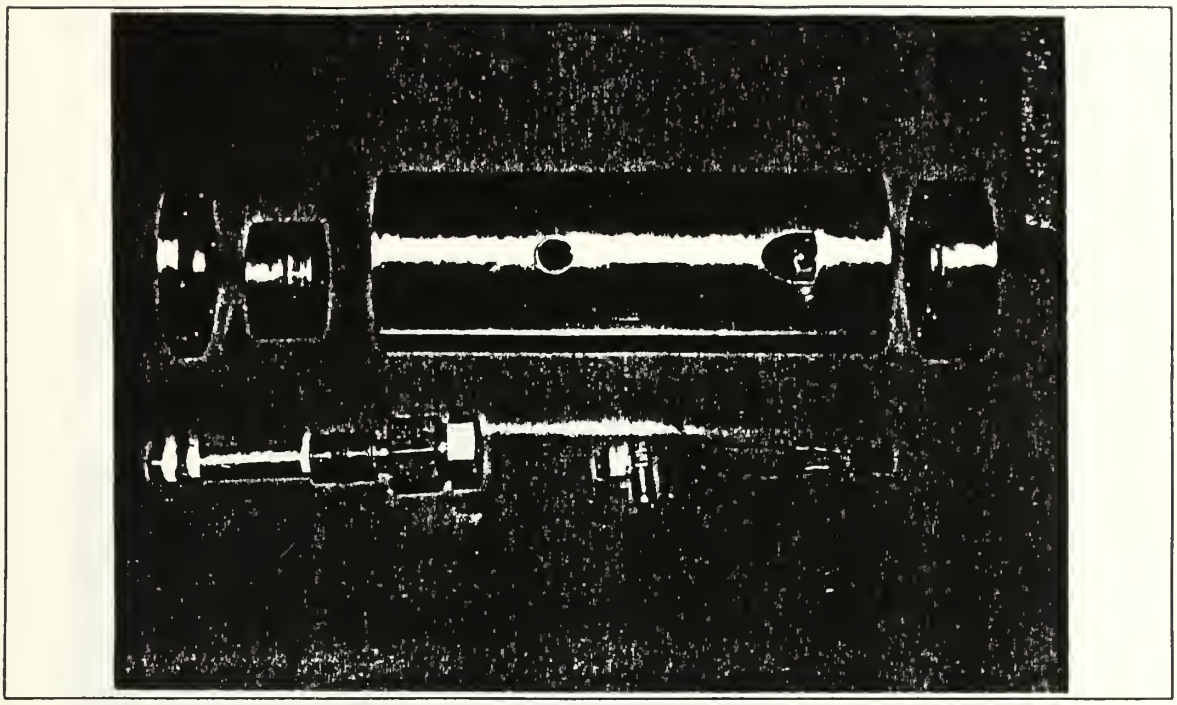


Figure III-1. Photograph of the Motor Components

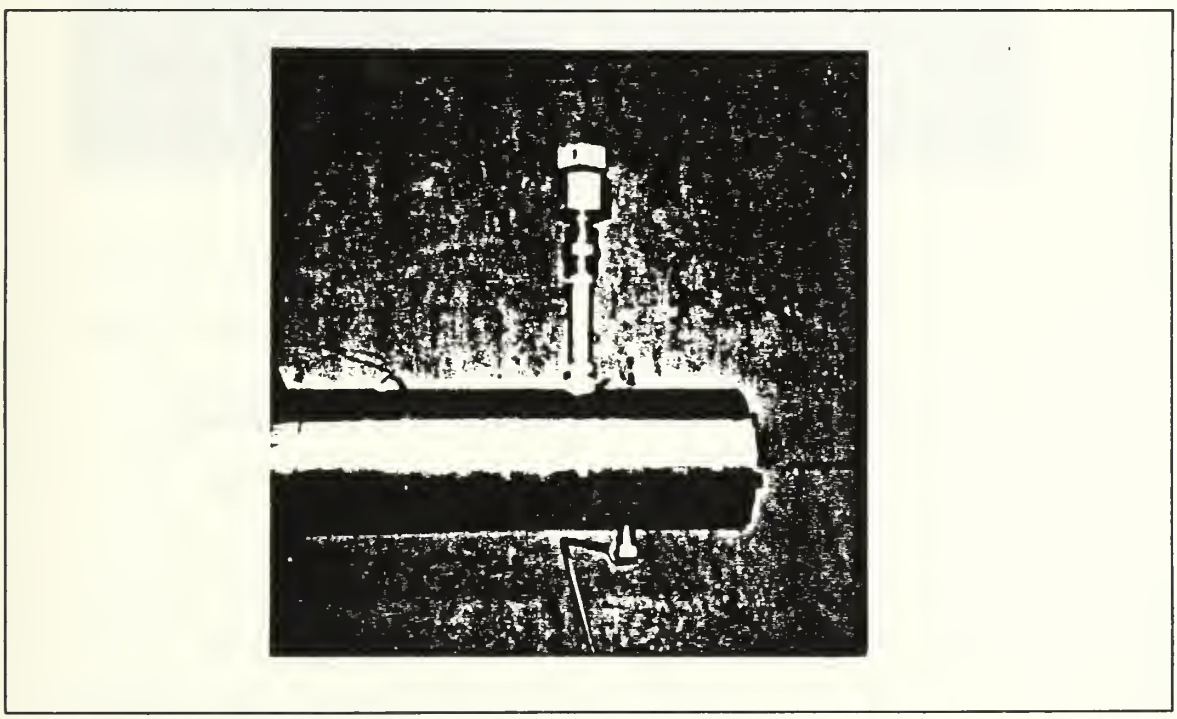


Figure III-2. Photograph of Installed Rocket Motor

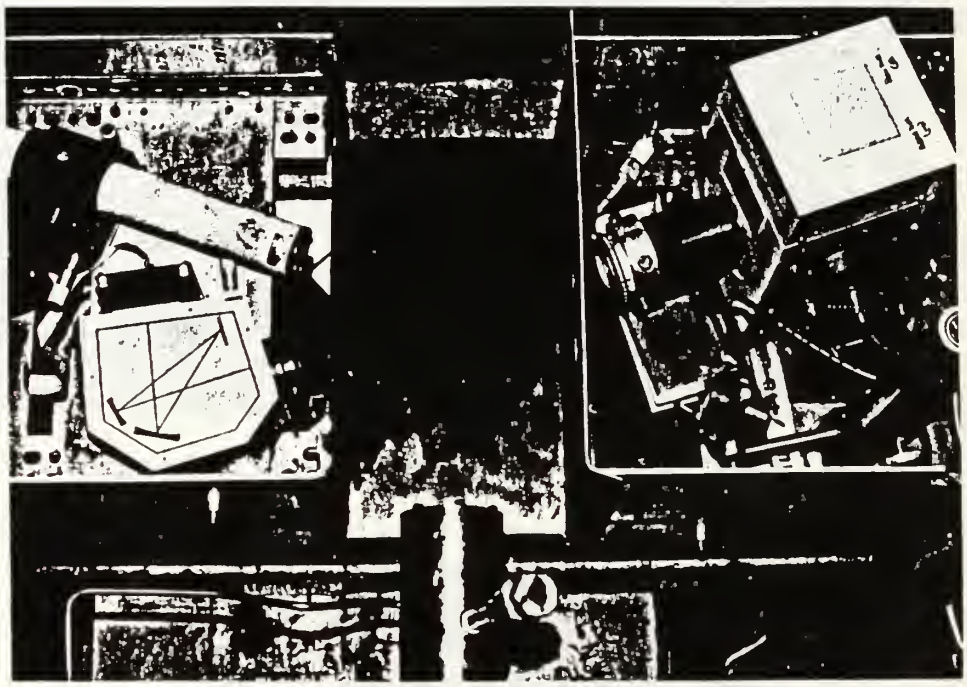


Figure III-3. Photograph of Light Transmittance System

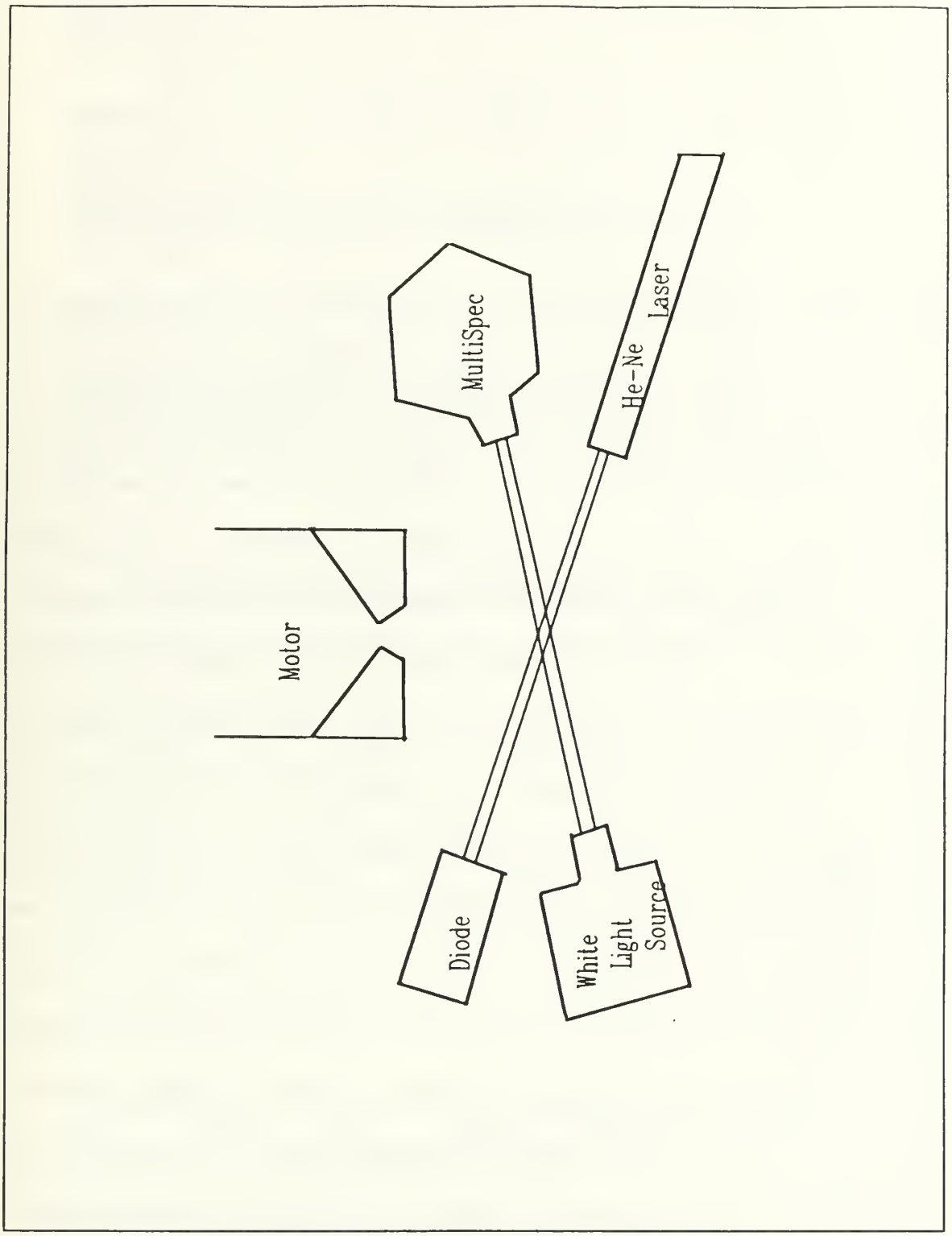


Figure III-4. Schematic Diagram of Light Transmittance Apparatus

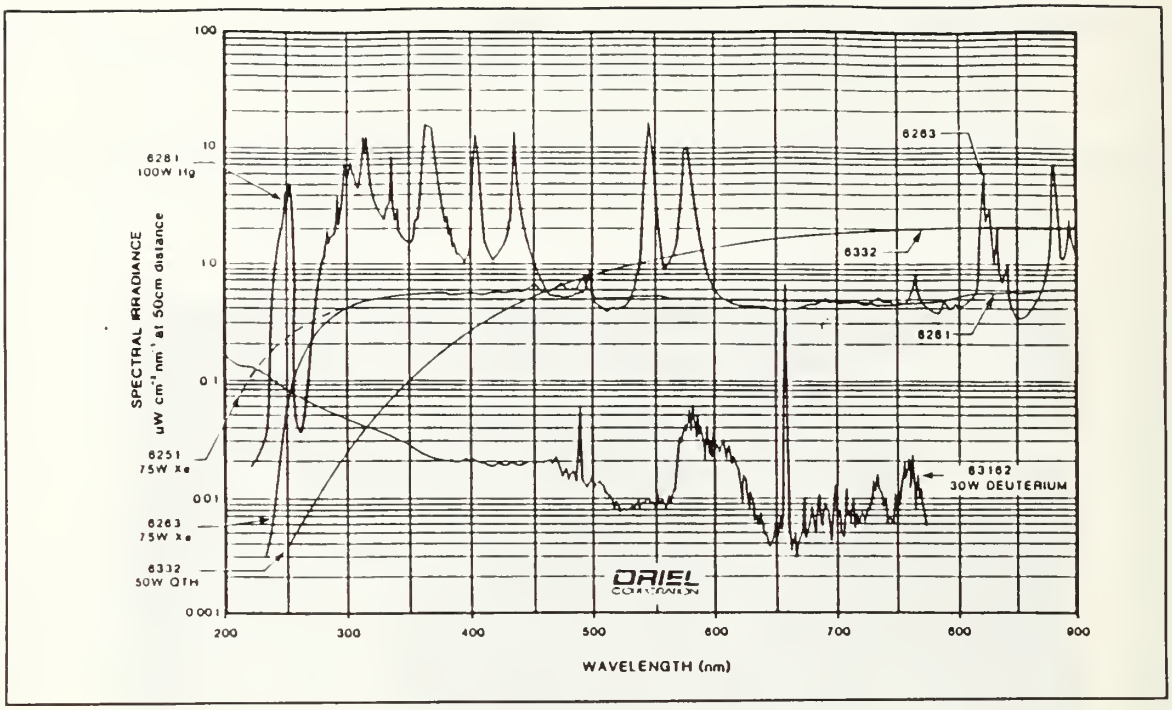


Figure III-5. Spectral Irradiance of the Hg Lamp [Ref. 9]

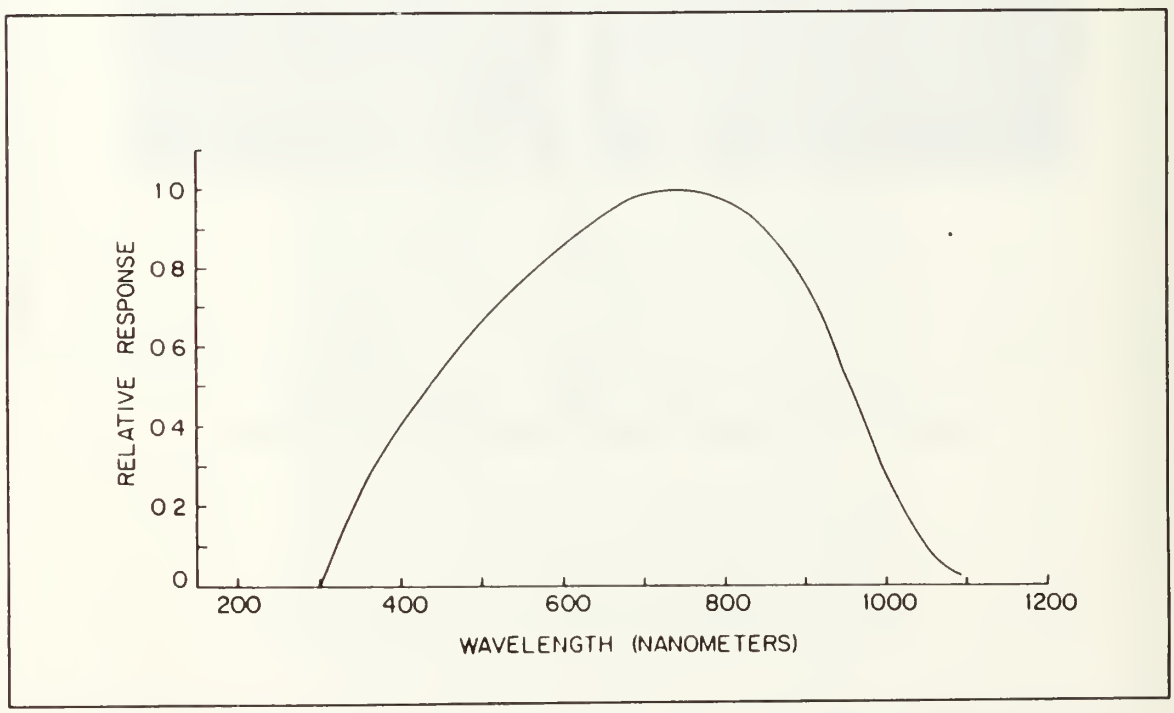


Figure III-6. Diode Spectral Response [Ref. 10]

IV. RESULTS AND DISCUSSION

A. INTRODUCTION

The purpose of this investigation was to measure the Sauter mean diameter (d_{32}) and to determine the refractive index (m) and the standard deviation (σ) of an assumed log-normal size distribution of particles in the exhaust plume of a small solid propellant rocket motor. The exhaust plume can contain a broad range of particle sizes, ranging from 0.01 μ to greater than 15 μ. However, most of the particles are thought to be smaller than 1 μ in diameter. Mie theory [Ref. 6] was used to find the extinction coefficients as a function of d_{32}, λ, m and σ. A mercury light source was used to provide multiple wavelengths for transmission measurements. Although the mercury lamp emits ten distinct wavelength peaks, only five were measured due to the diode insensitivity to the UV (See Figures III-5 and III-6). Ten independent transmittance ratios could be obtained from these five wavelength measurements. Initially, a He-Ne IR (λ=1.525) laser was also used in an attempt to provide a wider range of log-transmission ratios. However, the particles were small enough to result in transmittances of nearly 100%. Measurement uncertainty prevented use of this data. On the last test a He-Ne laser with λ=0.6328 was used. Although the measured transmittance was quite high (~96%) the data correlated well with that obtained using the Hg light source. Use of the sixth wavelength resulted in 15 (vs. 10) independent log-transmittance ratios for correlation with the extinction coefficient ratios. Because the extinction coefficient ratios become

insensitive to d_{32} for d_{32} greater than approximately 1 μ, the measurements had to be made in the edges of the plume where the larger particles are not thought to be present.

B. SYSTEM CALIBRATION

The computer program written by Harris [Ref. 11] for recording, reducing and plotting the data from the linear diode arrays was modified for this investigation. In this investigation measurements were first made of the intensities with no particles present. During the motor firing the transmittances were measured twice, once with the light sources on and once with them off. The latter measurement was made to determine if significant radiation was emitted from the plume at the wavelengths of the light sources.

The diode array was first aligned so that the five distinct peaks of the mercury light source were correctly positioned. To determine if the system was operating correctly, it was checked using a neutral density filter with a 30% obscuration. A measurement was first made to provide the intensities of the illumination source as a function of wavelength. A second measurement was then made with the neutral density filter inserted between the light source and the diode array. The transmittance at each wavelength was then calculated by dividing the second measurement by the first. The results showed that the diode array and data acquisition system worked correctly.

C. ROCKET MOTOR PLUME DATA

Seven experiments were conducted and a summary of the motor firings is tabulated in TABLE IV-1. Due to system failures, no data were obtained in four of these tests.

TABLE IV-1. SUMMARY OF MOTOR FIRINGS

Test No	Max Press	Location of Hg Light beam	Remarks
1	–	6" from Nozzle 1.0" above center	Data Trigger - failure
2	370 psig	"	1st Data
3	–	"	Data Trigger - failure
4	385 psig	"	2nd Data
5	–	13" from Nozzle center of plume	HP Computer - failure
6	410 psig	"	Contaminated - Windows
7	330 psig	7.25" from Nozzle 1.0" above center	3rd Data

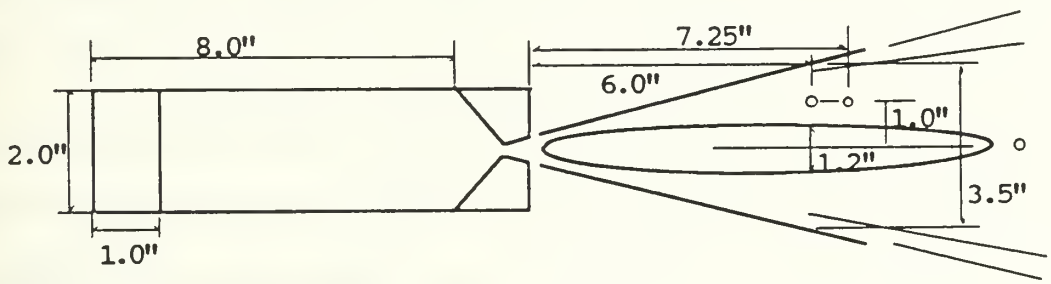


FIGURE IV-1. Configurations of the Motor and Plume

The exhaust plume was initially video recorded from above with a scaled plate positioned beneath the plume to determine the ideal positioning for the measurements. A sketch of the motor and plume is shown in Figure IV-1. An IR camera used in a related investigation also located the afterburning region within the exhaust plume. It was desired to make the transmission measurements in the outer regions of the plume to reduce the possibility of having large particles present and not to be within the afterburning region where high plume radiation is present. However, it was necessary to be close enough to the exhaust nozzle as possible to provide as steady a plume flowfield as possible. The measurement locations are shown Figure IV-1, 16-19 nozzle exit diameters (6-7.25") downstream and 5.25 nozzle exit radii (1.0") from the plume centerline.

The "lights-on"/"lights-off" measurements during the motor firings indicated that no significant plume radiation was present at the measurement location for the wavelengths of the illumination sources. Each run, therefore, provided two sets of data; one for 100% transmittance (before the firing) and the other with the plume particles present. Eight scans of the diode array were taken in 0.24 seconds. Any obviously bad scans were eliminated and the remaining scan voltages were averaged. The analog results are shown in Figures IV-2 through IV-7. The digital data was also recorded and is presented in APPENDIX A. Peak voltages on the array for each wavelength generally occurred over several diodes. During a motor firing some steering of the illuminating beam also occurs due to density gradients in the plume. The unsteadiness of the plume also resulted in some fluctuations in both the peak voltages and the diodes on which the peaks occurred.

TABLE IV-2. DIODE READINGS AND TRANSMITTANCE

	Wavelength,	λ=.365	λ=.4047	λ=.4358	λ=.5461	λ=.577
1	W/O Plume	217-221 (.00520)	341-346 (.00542)	436-448 (.00531)	789-798 (.00625)	888-897 (.00645)
	With Plume	213-222 (.00460)	339-346 (.00494)	436-446 (.00491)	787-799 (.00600)	890-901 (.00622)
	Transmittance	88.46 %	91.15 %	92.49 %	96.0 %	96.46 %
2	W/O Plume	219-227 (.00481)	344-348 (.00468)	439-446 (.00554)	787-802 (.00608)	887-901 (.00559)
	With Plume	220-228 (.00430)	345-348 (.00430)	438-443 (.00515)	789-799 (.00588)	889-898 (.00543)
	Transmittance	89.37 %	91.88 %	93.0 %	96.72 %	97.08 %
3	W/O Plume	214-224 (.00568)	340-343 (.00475)	434-444 (.00568)	784-799 (.00616)	885-899 (.00563)
	With Plume	217-223 (.00460)	340-344 (.00400)	438-444 (.00491)	789-800 (.00575)	888-903 (.00532)
	Transmittance	80.96 %	84.21 %	86.52 %	93.4 %	94.42 %

TABLE IV-3. LOG TRANSMISSION RATIOS

	1st run	2nd run	3rd run
$\lambda_{(.5770)}/\lambda_{(.3650)}$	0.294	0.264	0.272
$\lambda_{(.5461)}/\lambda_{(.3650)}$	0.333	0.297	0.323
$\lambda_{(.5770)}/\lambda_{(.4047)}$	0.389	0.350	0.334
$\lambda_{(.5461)}/\lambda_{(.4047)}$	0.441	0.394	0.397
$\lambda_{(.5770)}/\lambda_{(.4358)}$	0.462	0.408	0.396
$\lambda_{(.5461)}/\lambda_{(.4358)}$	0.523	0.460	0.471
$\lambda_{(.4358)}/\lambda_{(.3650)}$	0.637	0.646	0.686
$\lambda_{(.4047)}/\lambda_{(.3650)}$	0.756	0.754	0.814
$\lambda_{(.4358)}/\lambda_{(.4047)}$	0.843	0.857	0.843
$\lambda_{(.5770)}/\lambda_{(.5461)}$	0.883	0.889	0.841

In general, peak voltages were present on several diodes and then dropped off rapidly on either side. These peak voltages were then averaged. The diode numbers for each peak,the average voltages and the calculated transmittances are presented in TABLE IV-2. TABLE IV-3 presents the log-transmittance ratios.

Assuming the refractive index (with absorption index ~ 0) of the plume particles was independent of wavelength, extinction coefficients were calculated for each wavelength using the Mie code [Ref. 5] and are shown in Figure IV-8. Extinction coefficient ratios were then calculated as shown in Figure IV-9. The unknowns to be determined were m, σ and d_{32}. This was accomplished in an iterative manner, starting with expected values taken from the literature. The iteration scheme is shown in Figure IV-10. In order to determine the best fit with the experimental data, a regression analysis method [Ref. 12] was used. The log-transmittance ratios were plotted against the extinction coefficient ratios. A linear least-squares fit of the data was then made; a perfect fit having a slope of unity and an R^2 of unity. R^2 is defined by

$$R^2 = \frac{\Sigma(y_{est}-\bar{y})^2}{\Sigma(y-\bar{y})^2} = \frac{Explained\text{-}variation}{Total\text{-}variation}$$

"R^2 can be interpreted as the fraction of the total variation which is explained by the least-squares regression line. If the total variation is all explained by the regression line, i.e. if $R^2 = 1$, we say that there is perfect linear correlation (and in such case also perfect linear regression). On the other hand if the total variation is all unexplained then the explained variation is zero and so R=0. In practice the quantity R^2, sometimes called

TABLE IV-4 . REGRESSION ANALYSIS FOR THE RUNS

		1st plume	2nd plume	3rd plume	Remarks
1	X-Coefficient(slope) Err from Slope R squared	0.8589 0.0289 0.9455	0.8841 0.0176 0.9809	0.8759 0.0229 0.9671	d_{32} =.09 σ =1.5 m= 1.7-0i
2	X-Coefficient(slope) Err from Slope R squared	0.9263 0.0172 0.9790	0.9512 0.0118 0.9905	0.9434 0.0131 0.9883	d_{32} =.12 σ =1.5 m =1.7-0i
3	X-Coefficient(slope) Err from Slope R squared	0.9991 0.0129 0.9868	1.0235 0.0231 0.9599	1.0162 0.0186 0.9736	d_{32} =.15 σ =1.5 m =1.7-0i
4	X-Coefficient(slope) Err from Slope R squared	0.9061 0.0203 0.9716	0.9310 0.0117 0.9910	0.9231 0.0154 0.9841	d_{32} =.15 σ =1.3 m =1.7-0i
5	X-Coefficient(slope) Err from slope R squared	1.0628 0.0219 0.9553	1.0860 0.0395 0.8622	1.0785 0.0357 0.8855	d_{32} =.15 σ =1.7 m =1.7-0i
6	X-Coefficient(slope) Err from Slope R squared	0.9959 0.0102 0.9916	1.0199 0.0229 0.9596	1.0121 0.0208 0.9662	d_{32} =.12 σ =1.7 m =1.7-0i
7	X-Coefficient(slope) Err from Slope R squared	0.9663 0.0092 0.9935	0.9904 0.0169 0.9790	0.9824 0.0176 0.9769	d_{32} =.15 σ =1.5 m =1.5-0i
8	X-Coefficient(slope) Err from Slope R squared	1.0174 0.0155 0.9805	1.0417 0.0271 0.9433	1.0346 0.0214 0.9641	d_{32} =.15 σ =1.5 m =1.9-0i
9	X-Coefficient(slope) Err from Slope R squared	0.9736 0.0816 0.9948	0.9976 0.0186 0.9744	0.9895 0.0191 0.9723	d_{32} =.12 σ =1.7 m =1.5-0i
10	X-Coefficient(slope) Err from Slope R squared	1.0266 0.0146 0.9818	1.0505 0.0296 0.9294	1.0429 0.0259 0.9451	d_{32} =.12 σ =1.7 m =1.9-0i
11	X-Coefficient(slope) Err from Slope R squared	0.9771 0.0100 0.9925	1.0000 0.0182 0.9763	0.9931 0.0170 0.9782	d_{32} =.15 σ =1.5 m =1.63-0i

the coefficient of determination, lies between 0 and 1" [Ref 13]. The particle refractiveindex was varied from 1.5 to 1.9 and σ from 1.3 to 1.7 (see TABLE IV-4 for representative results). This iteration process was accomplished using the ten wavelength ratios provided by the mercury light source and resulted in d_{32}=0.15 , σ=1.5 and m=1.63. The extinction coefficients and extinction coefficient ratios shown in Figures IV-8 and IV-9 were calculated using these values.

In the above process it was necessary to estimate how accurately the values of d_{32}, σ and m could be determined. This was accomplished by perturbing each variable independently about the nominal values given above and observing the changes in the plotted fit to the data and the values of X-coefficient. The results are shown in Figures IV-11 through IV-13 and in TABLE IV-5. From this analysis, for 1 % variation in X-coefficient (Slope) the measured values of d_{32}, σ and m were determined to be as follows:

$$d_{32} = 0.150 \pm 0.006 \ \mu$$

$$\sigma = 1.50 \pm 0.04$$

$$m = 1.63 \pm 0.13$$

It is seen from these results that the multiple-wavelength transmission method (for the wavelengths used and the particle sizes present) can determine σ and d_{32} quite accurately and without much sensitivity to m. The refractive index cannot be determined as accurately using the present system.

Using the above values for d_{32}, σ and m, the data from all three motor firings are shown in Figure IV-14 for the five wavelengths of the mercury light source. The test-to test data were observed to be very repeatable. Another aspect of the technique utility is

TABLE IV-5. ESTIMATES OF MEASUREMENT ACCURACY, RUN 2

	X-Coefficient (R^2)	Estimated Accuracy (1 % deviation)
Sensitivity to d_{32} (Fig. IV-11)		
= 0.144 μ	0.990 (0.980)	
= 0.150 μ	1.000 (0.982)	± 0.006
= 0.155 μ	1.016 (0.963)	
Sensitivity to σ (Fig. IV-12)		
= 1.47	0.990 (0.971)	
= 1.50	1.000 (0.982)	± 0.04
= 1.54	1.012 (0.967)	
Sensitivity to m (Fig. IV-13)		
= 1.50	0.989 (0.979)	
= 1.63	1.000 (0.982)	± 0.13
= 1.70	1.023 (0.959)	

related to the accuracy of the measured transmittances. The required accuracy increases as λ increases and as the spread between the λ's decreases. This can be seen in Figure IV-14. The accuracy of the transmittance measurements was approximately 0.5 %. The resulting uncertainty bands for $\ln Tr(\lambda_5)/\ln Tr(\lambda_1)$ are much less than for $\ln Tr(\lambda_5)/\ln Tr(\lambda_4)$ where the wavelengths are much more closely spaced. The difference in wavelengths between λ_5 and λ_4 and between λ_3 and λ_2 are approximately equal (.031 μ). However, the log transmittance ratios for the lower wavelengths result in less uncertainty due to the lower values of transmittance. The data obtained in test 3 using the fifteen log-transmittance ratios provided by both the mercury and He-Ne light sources are shown in Figure IV-15. The additional ratios correlated well with the ten mercury lamp ratios and increased confidence in the data.

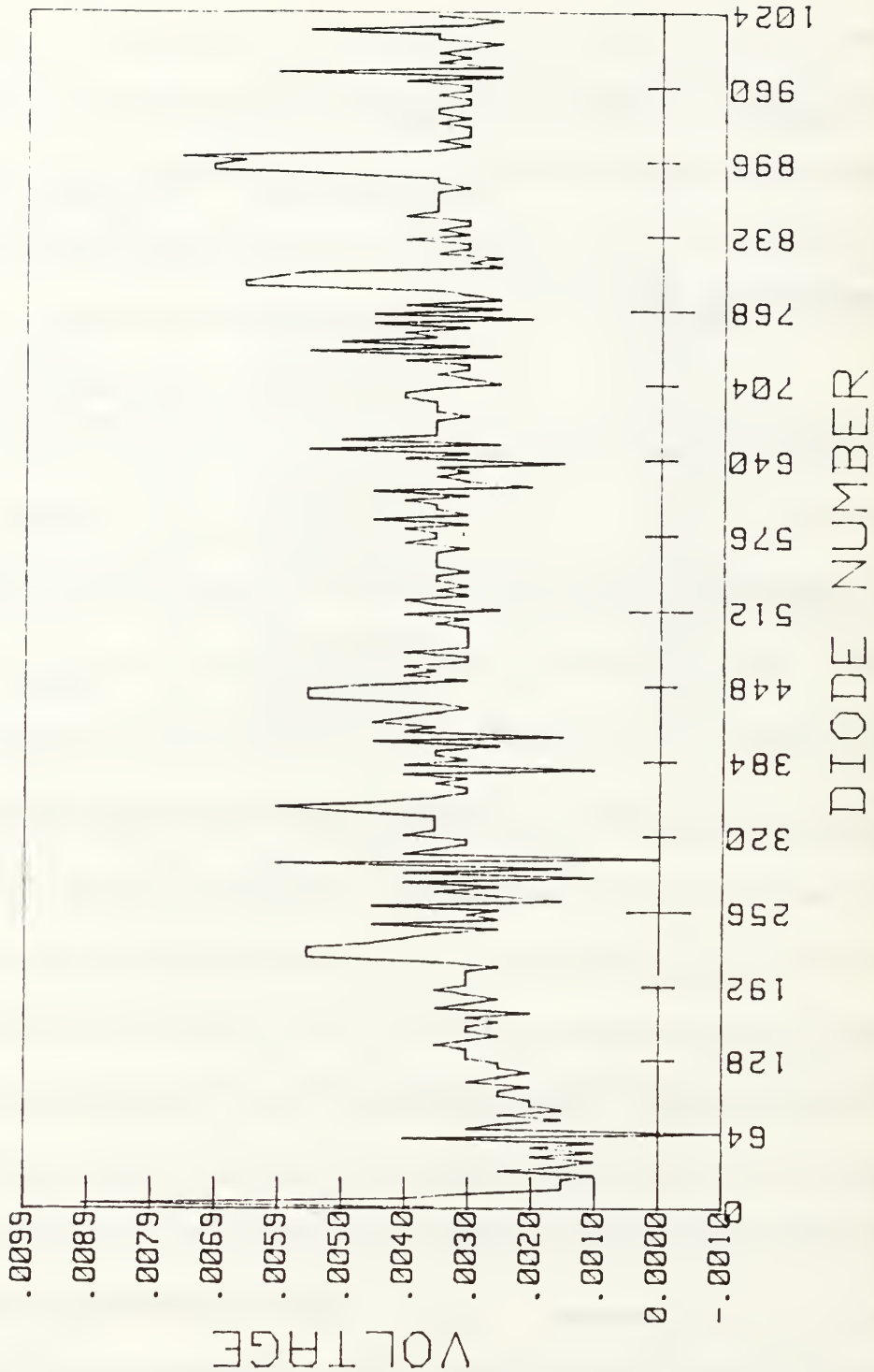


Figure IV-2. Voltage vs. Diode Number Run 1 without Plume

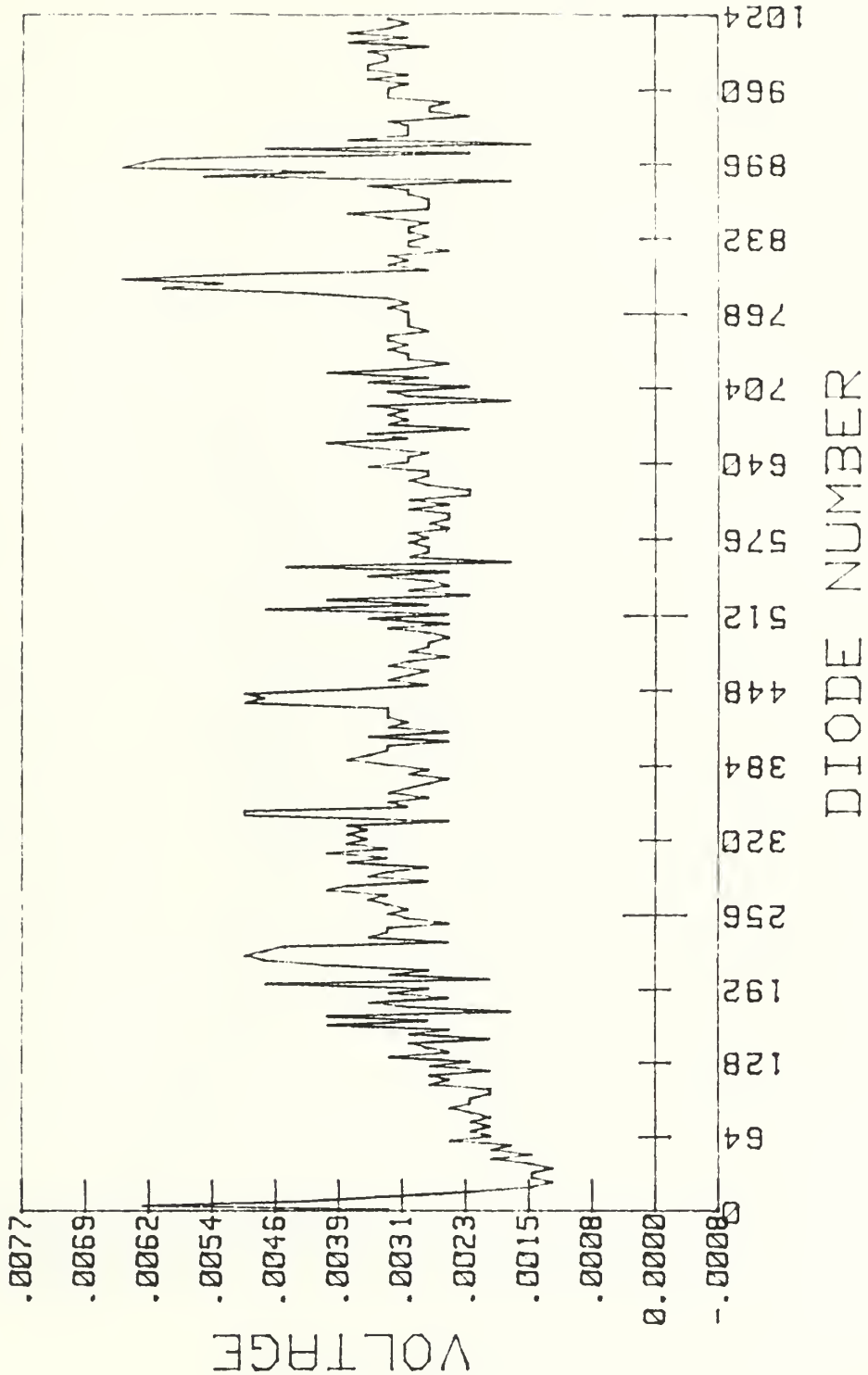


Figure IV-3. Voltage vs. Diode Number, Run 1, in Plume

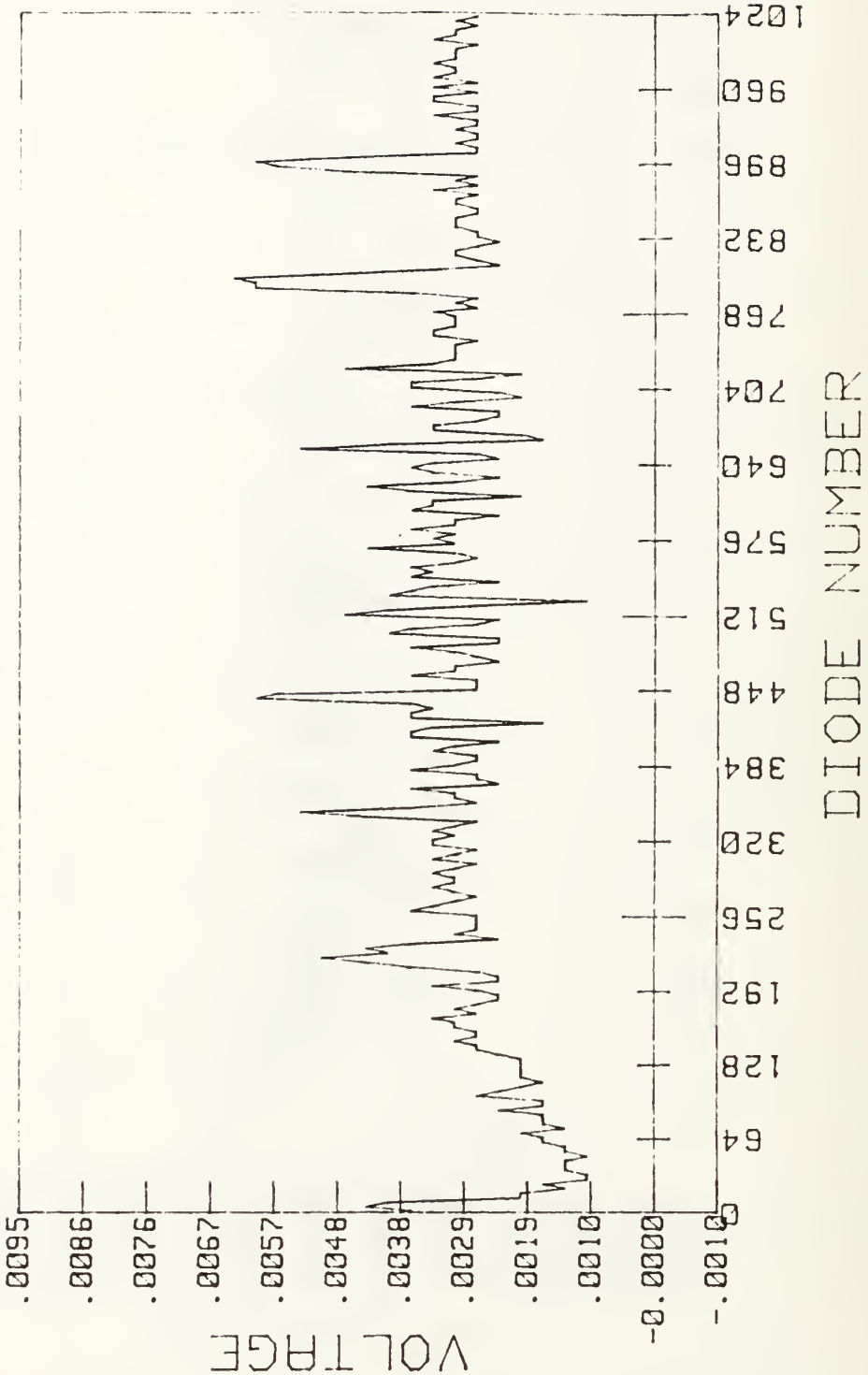


Figure IV-4. Voltage vs. Diode Number, Run 2, without Plume

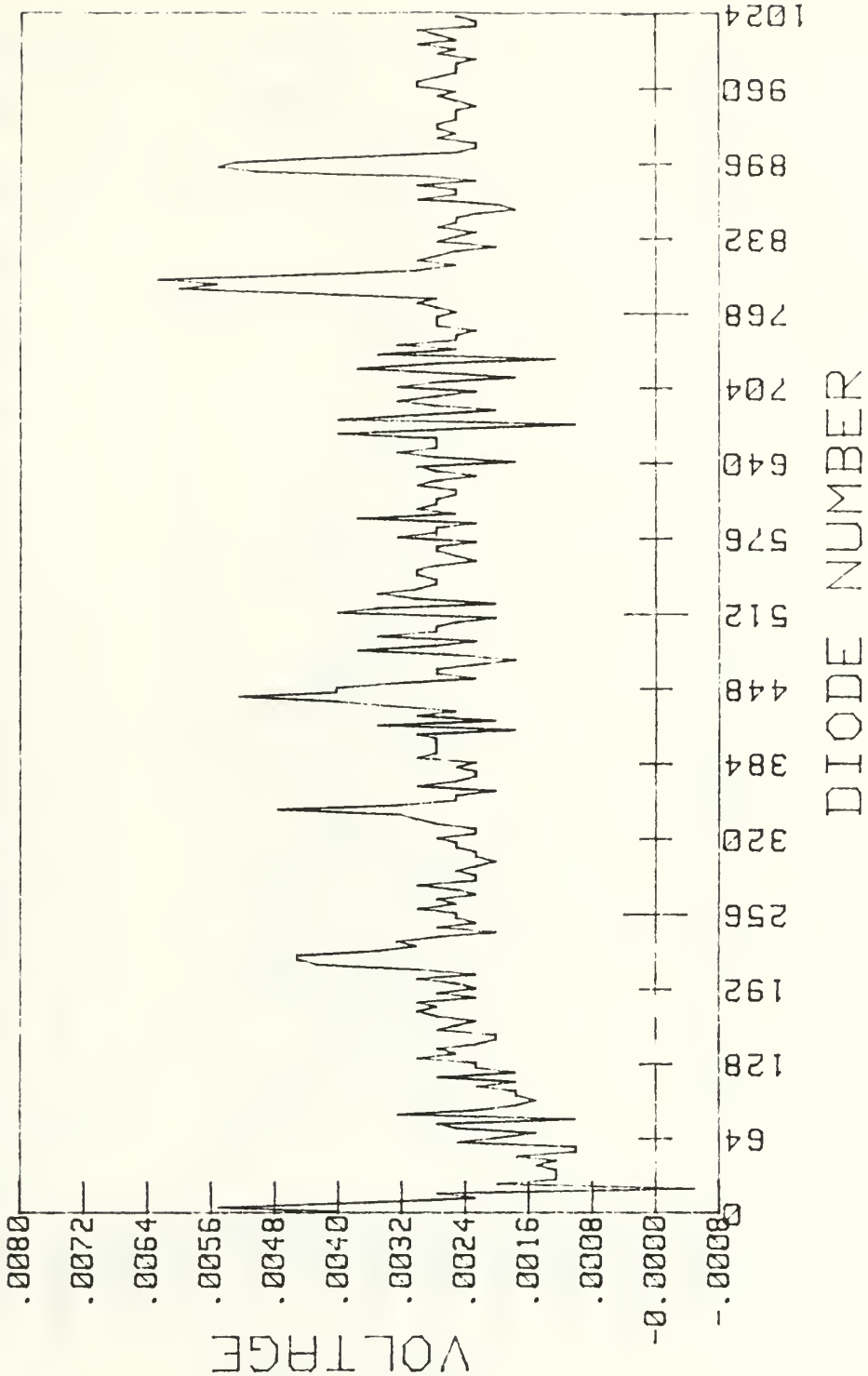


Figure IV-5. Voltage vs. Diode Number, Run 2, in Plume

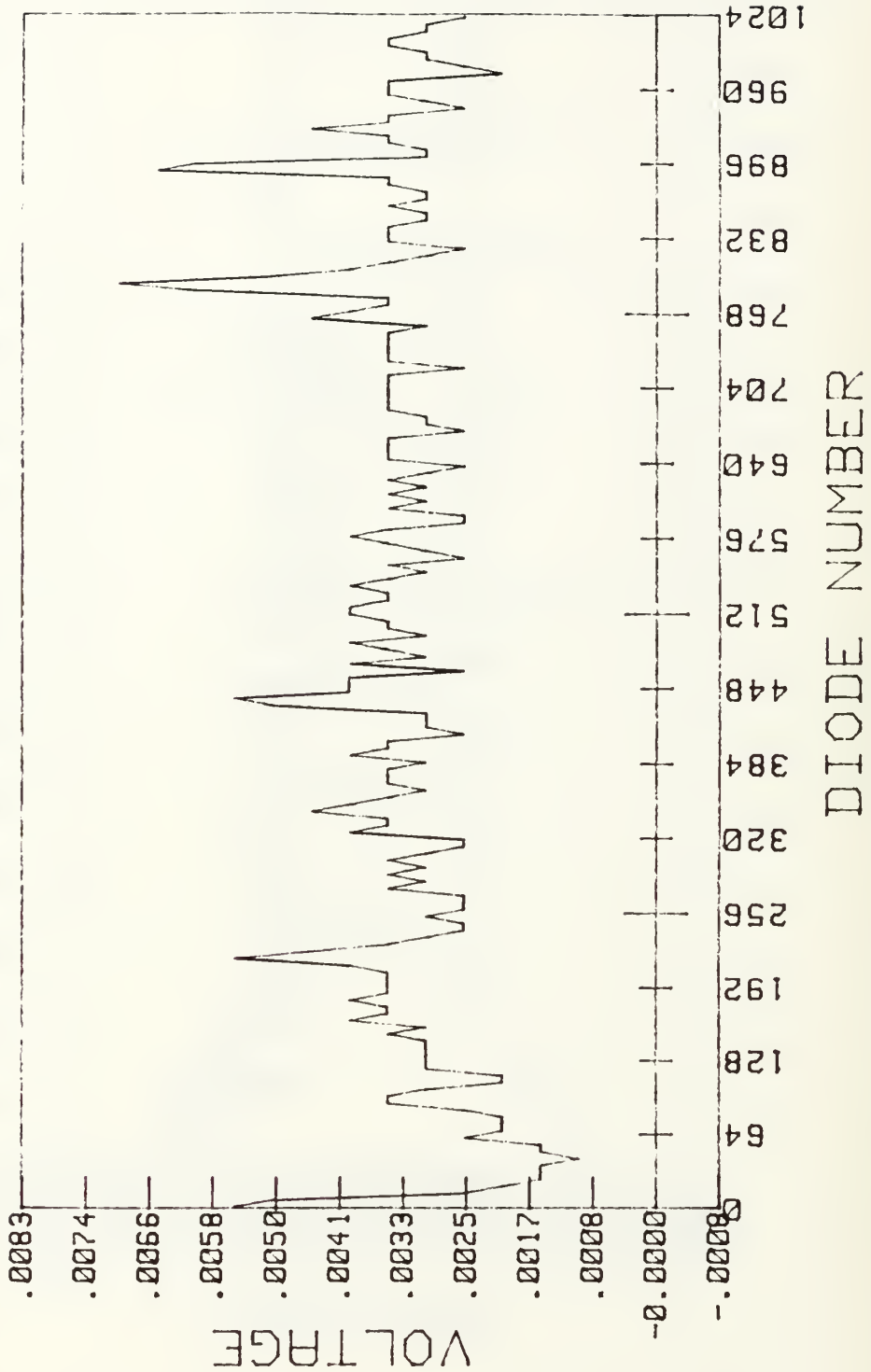


Figure IV-6. Voltage vs. Diode Number, Run 3, without Plume

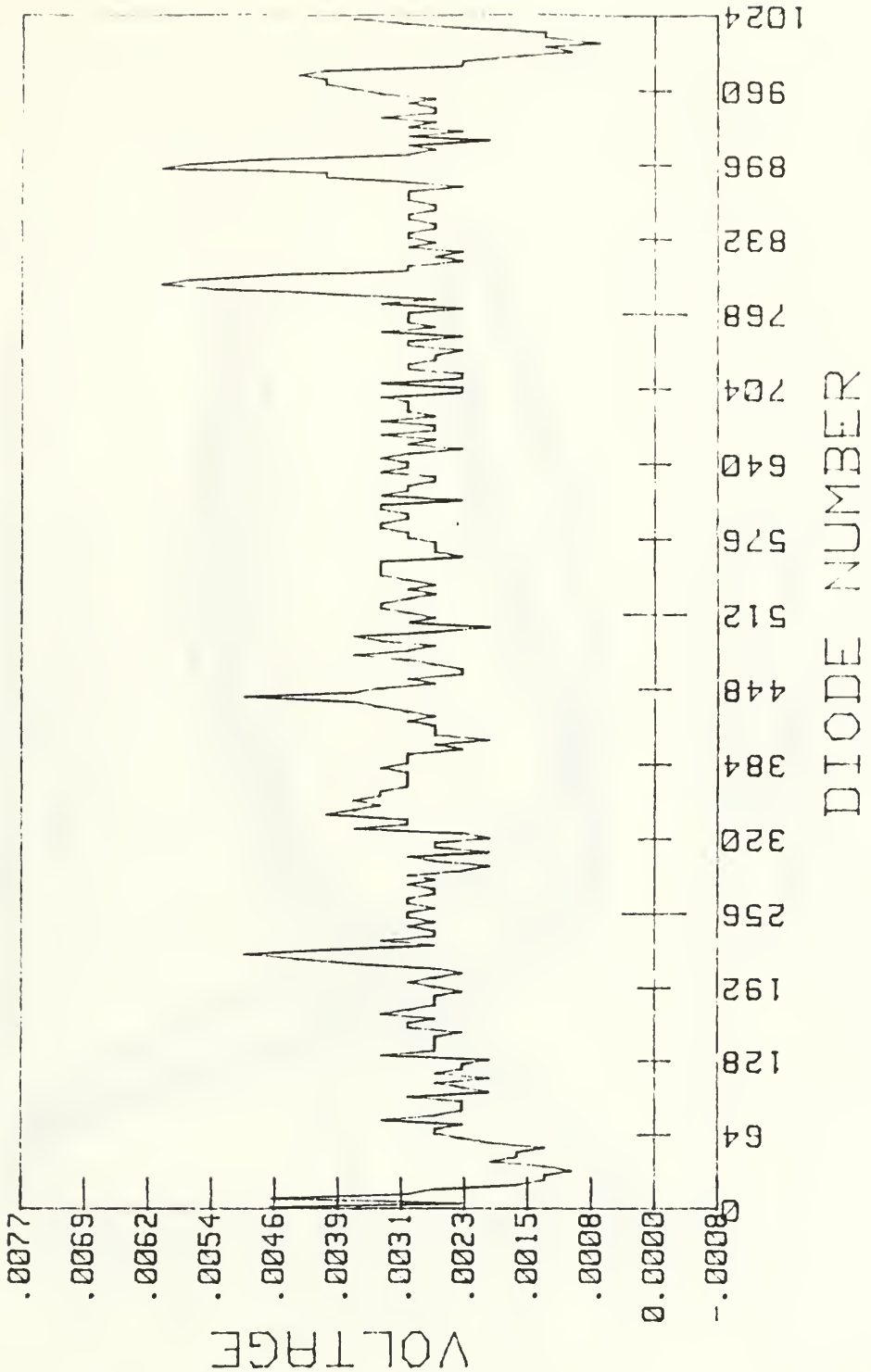


Figure IV-7. Voltage vs. Diode Number, Run 3, in Plume

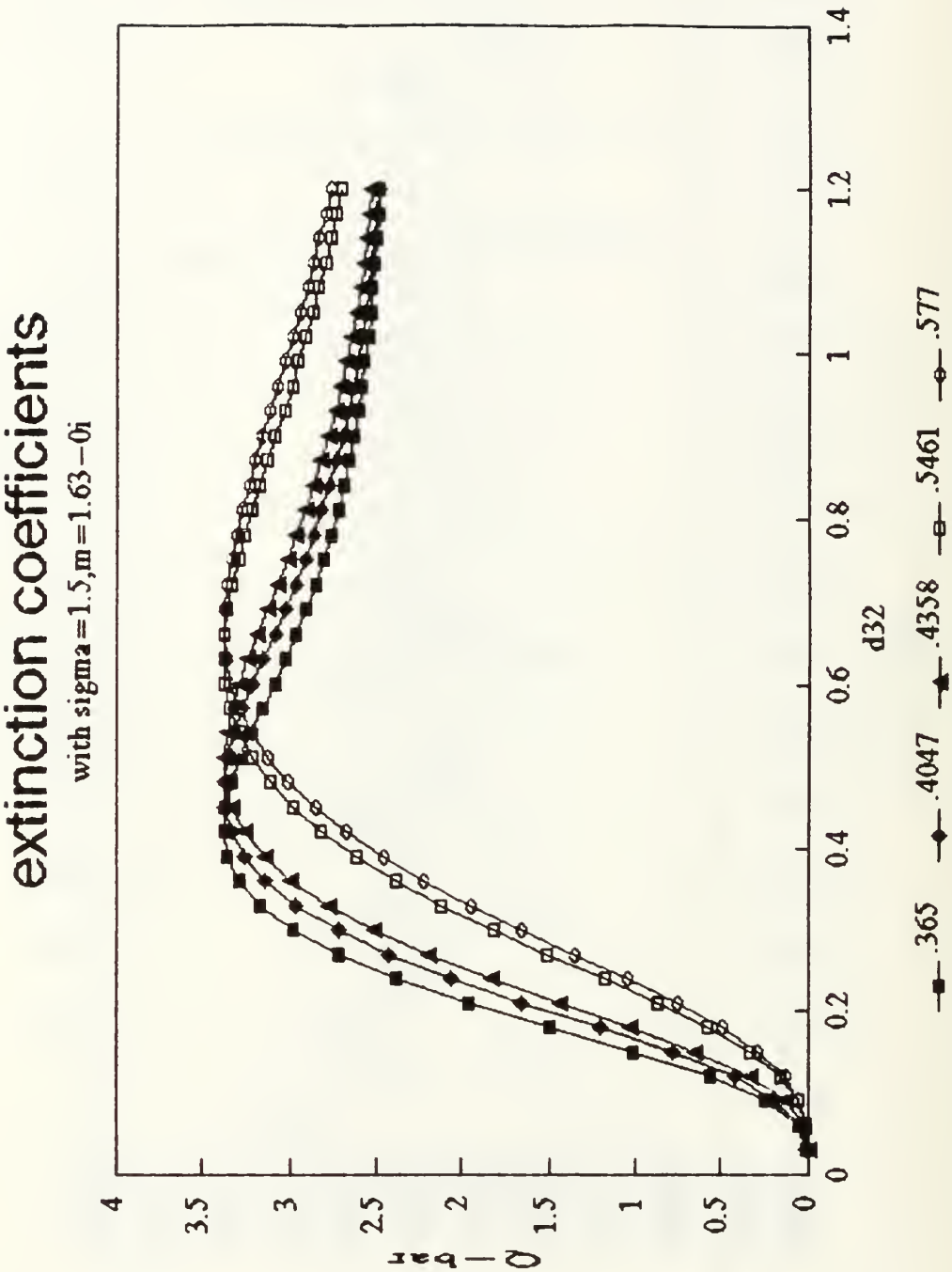


Figure IV-8. Extinction Coefficients

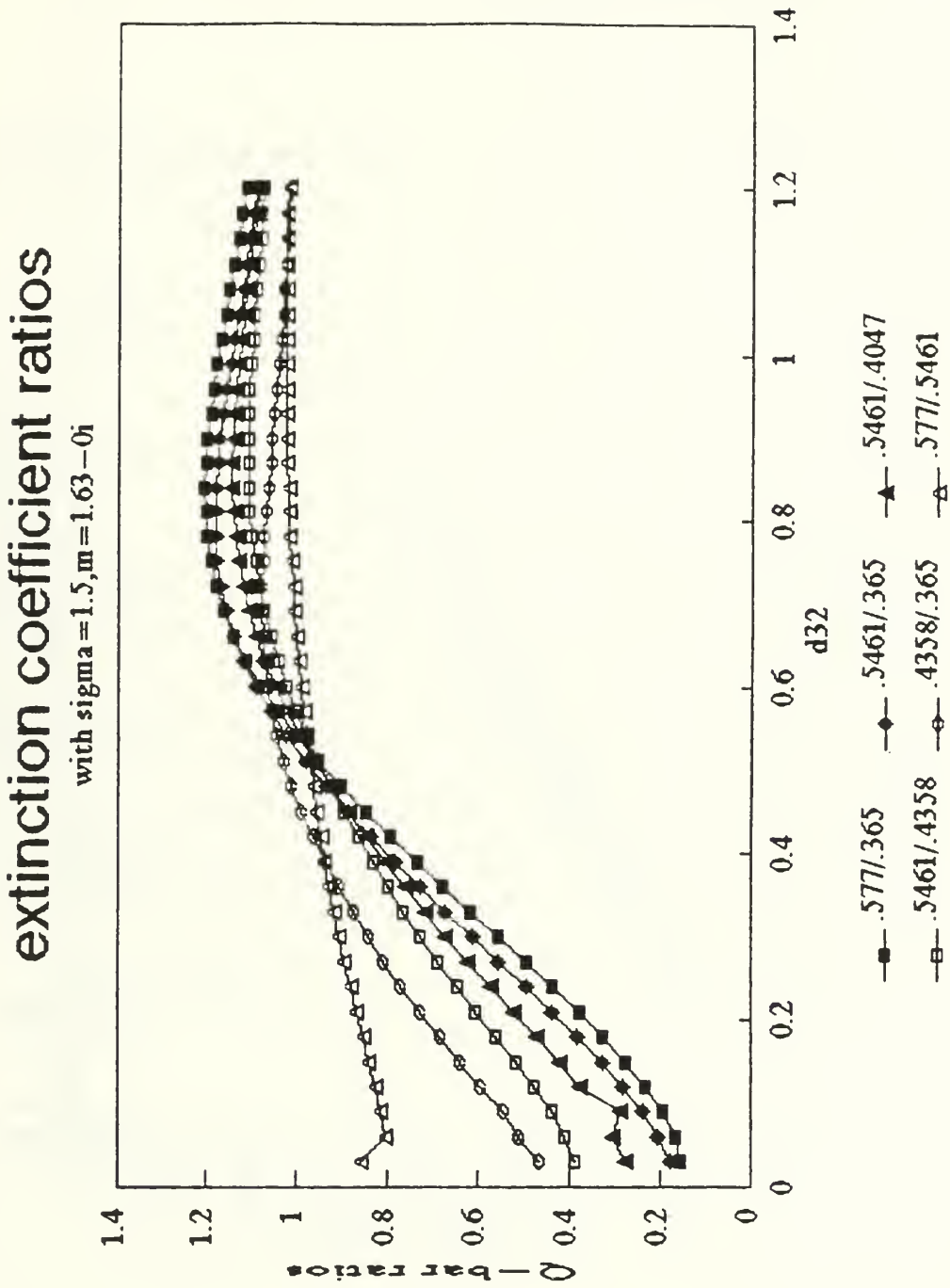


Figure IV-9. Extinction Coefficient Ratios

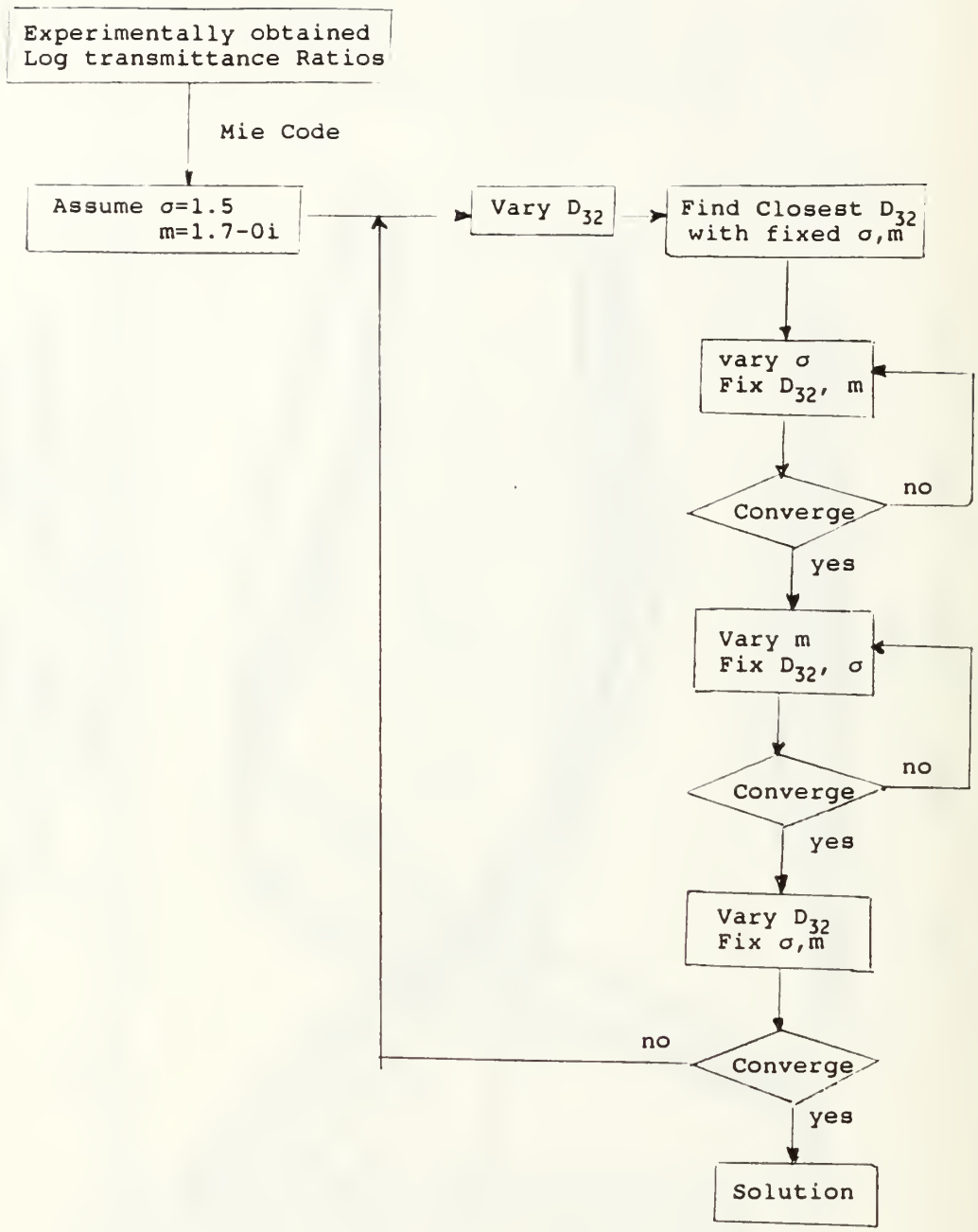


Figure IV-10. Iteration Flow Scheme

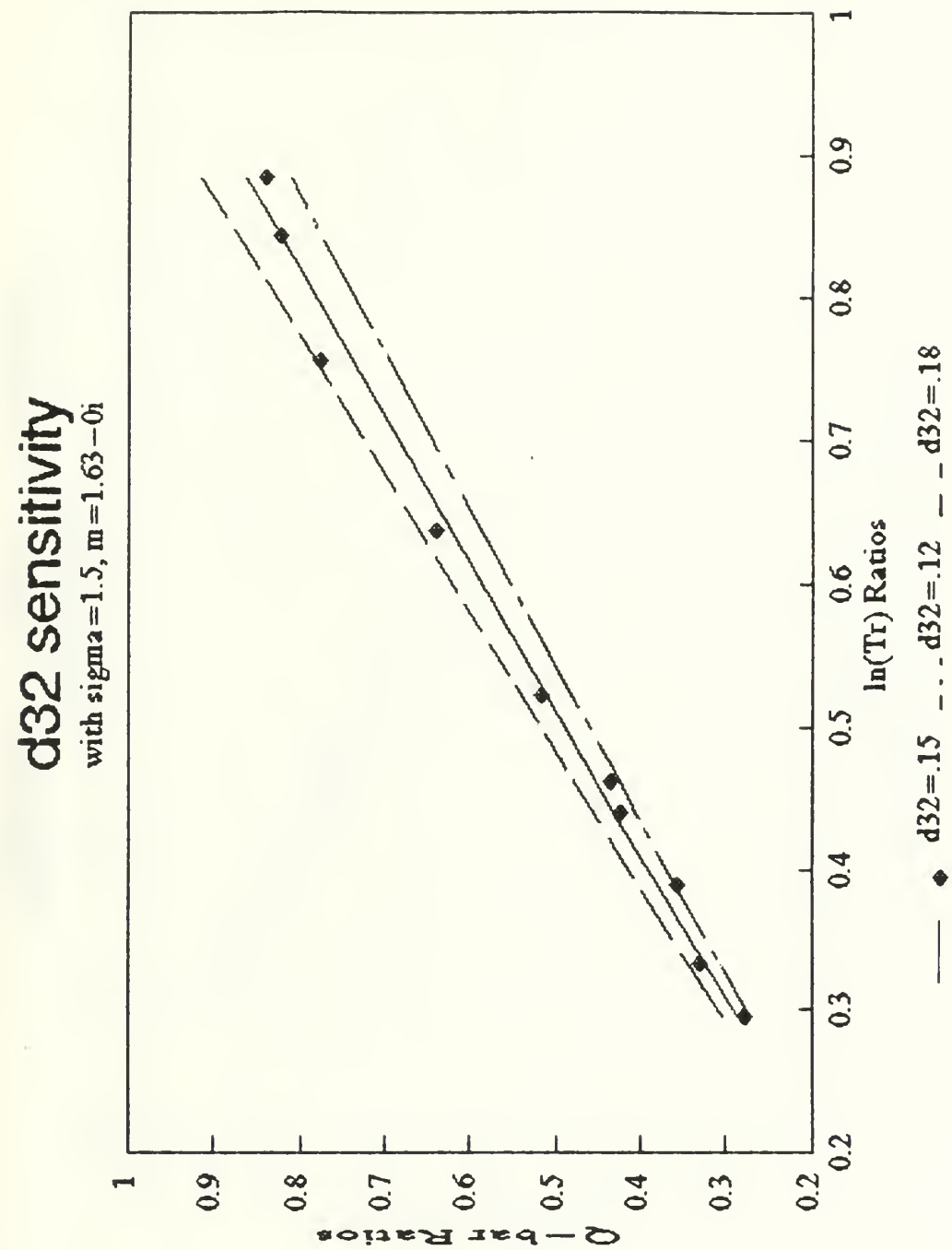


Figure IV-11. Data Correlation Sensitivity for Specified D_{32}, Run 1

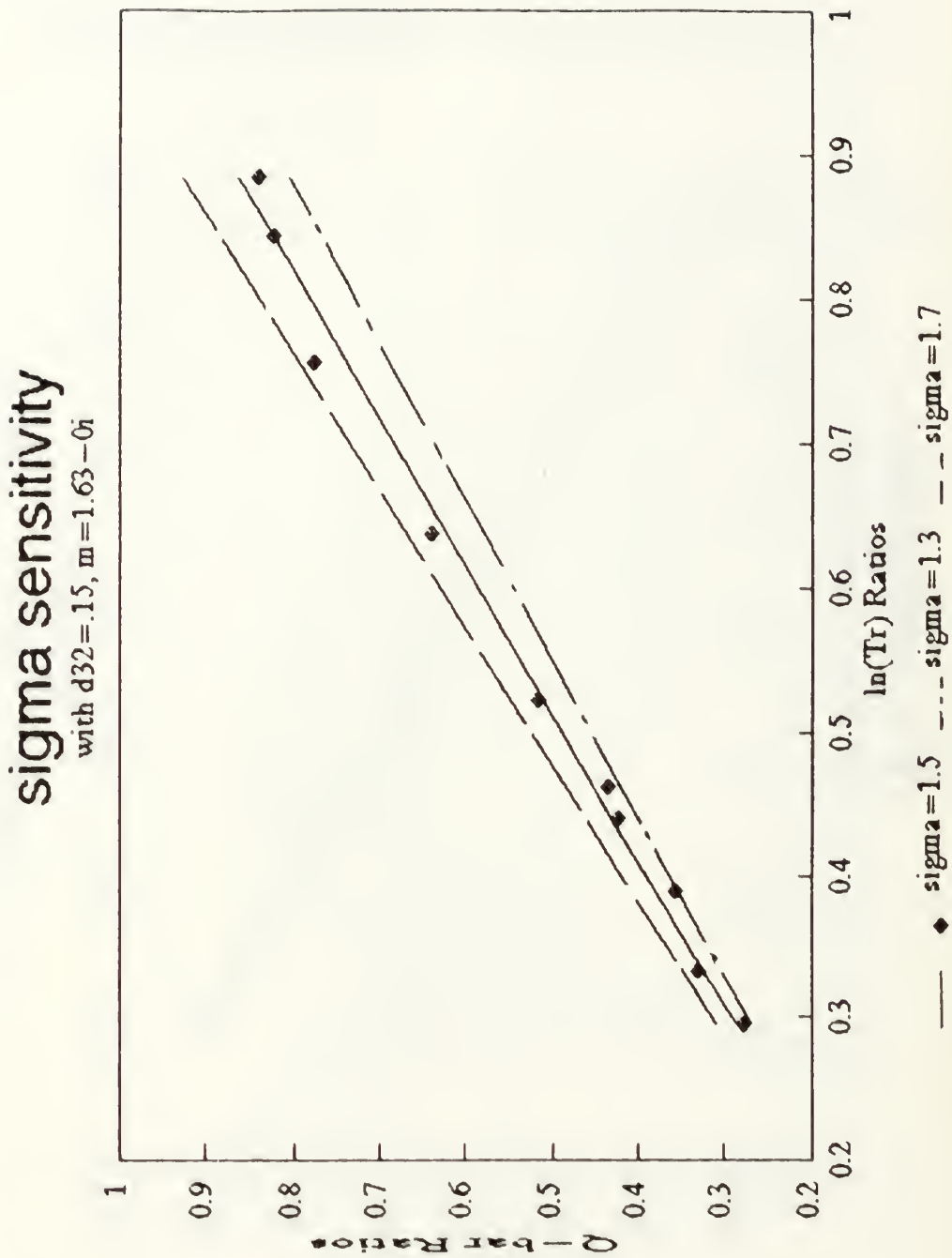


Figure IV-12. Data Correlation Sensitivity for Specified σ, Run 1

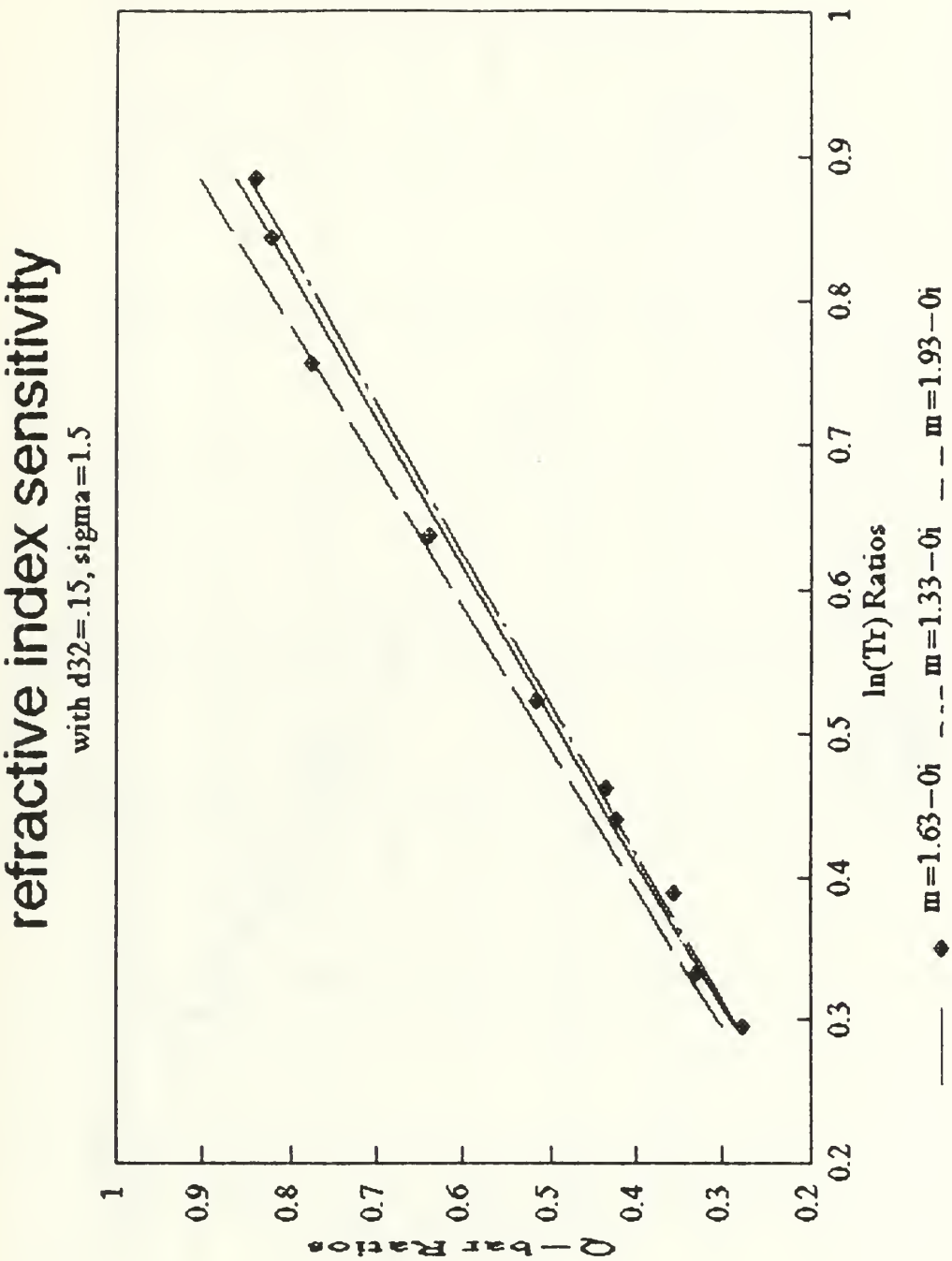


Figure IV-13. Data Correlation Sensitivity for Specified m, Run 1

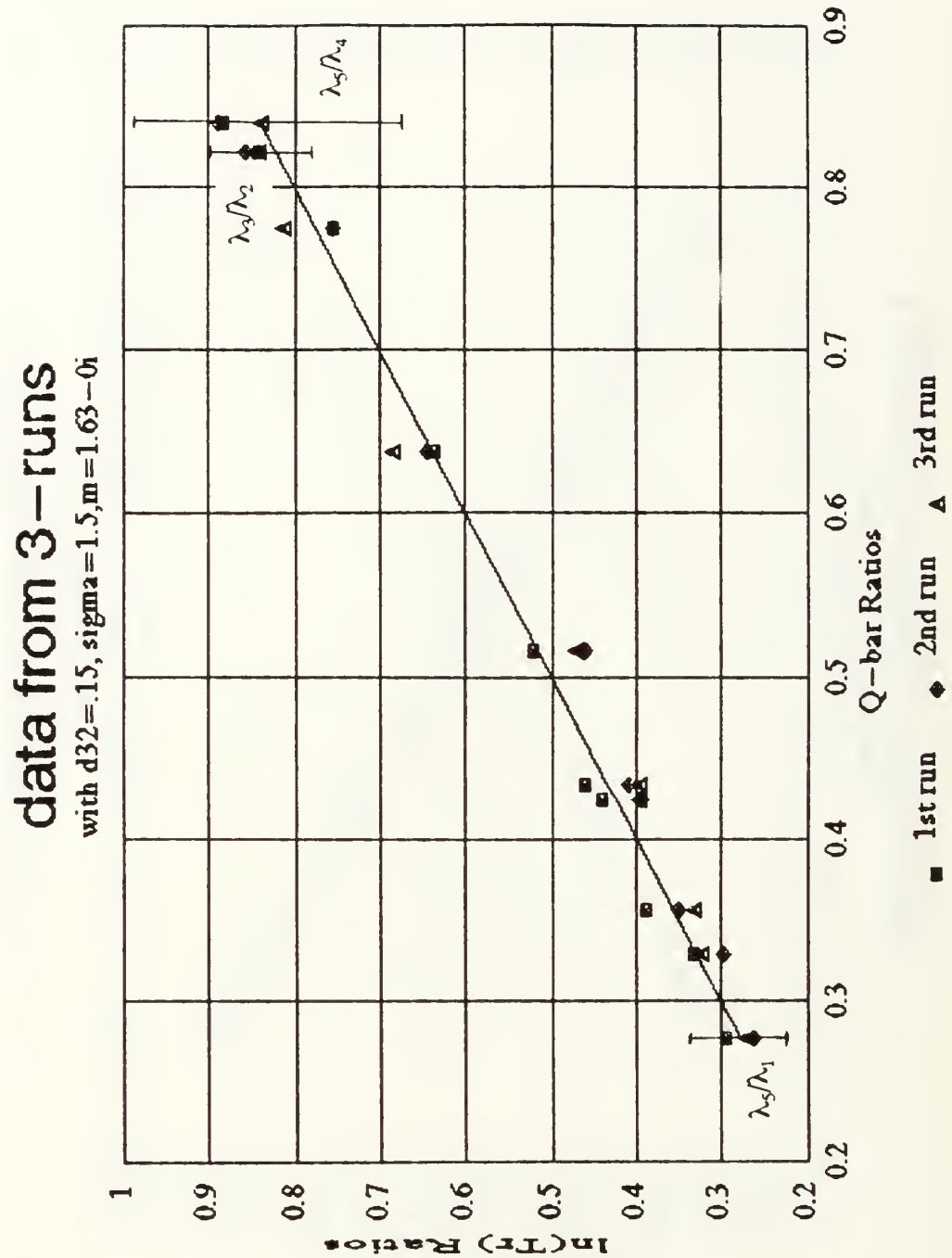


Figure IV-14. Log Transmission vs. Extinction Coefficient Ratios, Run 1,2 & 3

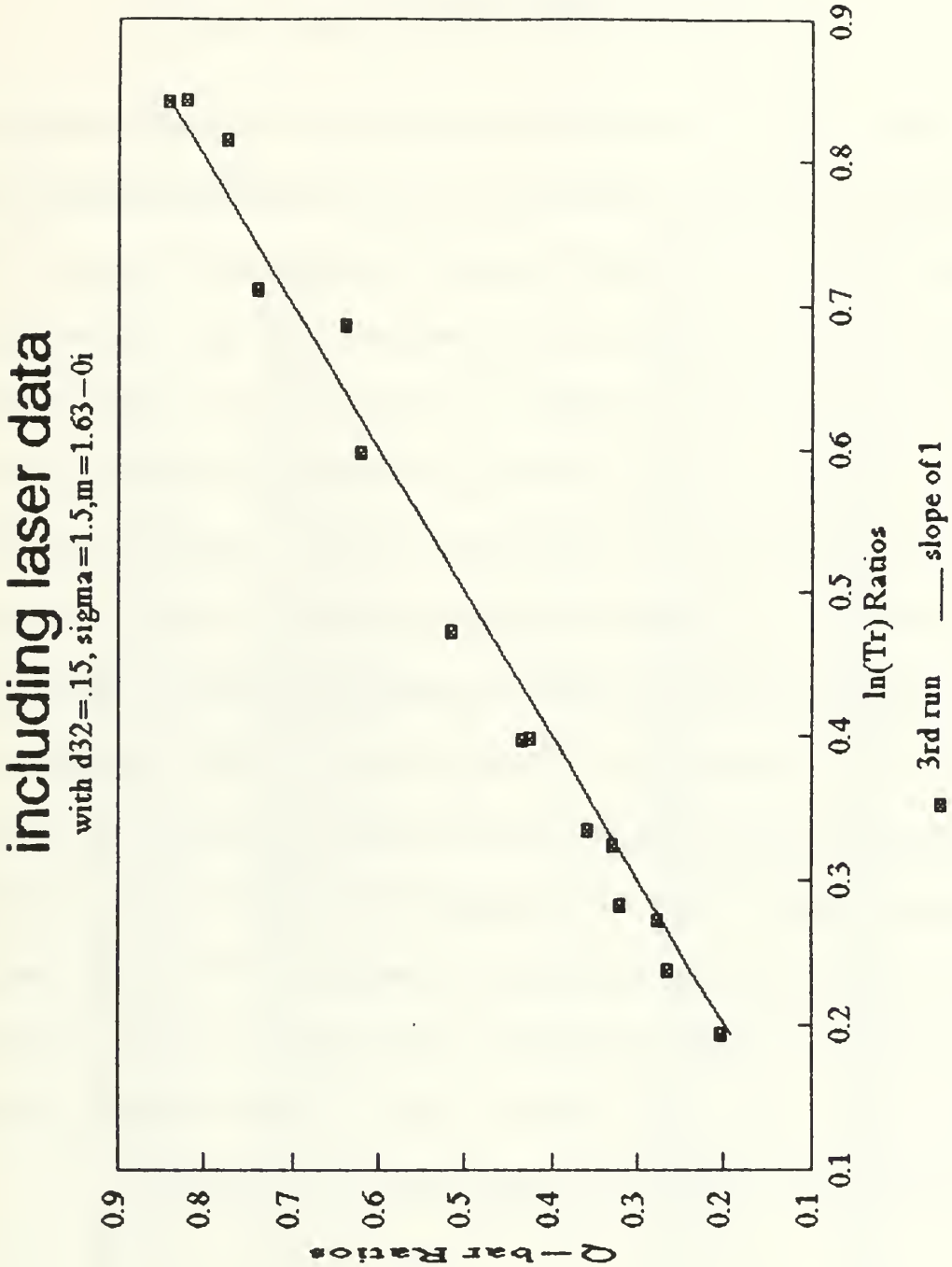


Figure IV-15. Log Transmission vs. Extinction Coefficient Ratios, Including 0.6328 μ Laser Data, Run 3

V. CONCLUSIONS AND RECOMMENDATIONS

The results of this investigation have shown that the multiple-wavelength light transmission measurement technique can be used to obtain the Sauter mean diameter and standard deviation (of an assumed log-normal size distribution) of the small particles present in the edge of a plume from a solid propellant rocket motor. The technique was shown to be more sensitive to changes in d_{32} and σ than to m. The values measured for Al_2O_3 in the plume of a small motor using a 4.7% aluminized GAP/AP propellant were $d_{32} = 0.150 \pm 0.006\ \mu$, $\sigma = 1.50 \pm 0.04$ and $m = 1.63 \pm 0.13$. The good correlation of the data indicated that only submicron particles were present in the edge of the plume.

Subsequent work should consider the employment of shorter wavelengths in order to provide lower transmittances. This would result in reducing the uncertainties in the log-transmittance ratios which occur when the measured transmittances are high and not adequately separated. This could be accomplished by changing the grating and by using a diode array which has appropriate spectral response in the UV. In addition, more rapid scanning of the diode array would permit a larger number of sweeps to be made in a shorter time. This would reduce the effects of plume fluctuations during the measurements and would provide a larger sample for data averaging.

APPENDICES

A. DIODE READINGS

** 1ST RUN W/O PLUME DATA **
** DIODE vs. VOLTAGE

210.0	.0035
211.0	.0030
212.0	.0025
213.0	.0035
214.0	.0030
215.0	.0045
216.0	.0045
217.0	.0055
218.0	.0055
219.0	.0045
220.0	.0050
221.0	.0055
222.0	.0035
223.0	.0045
224.0	.0045
225.0	.0055
335.0	.0035
336.0	.0035
337.0	.0035
338.0	.0035
339.0	.0040
340.0	.0035
341.0	.0050
342.0	.0055
343.0	.0055
344.0	.0055
345.0	.0060
346.0	.0050
347.0	.0045
348.0	.0045
349.0	.0045
350.0	.0030
351.0	.0040
352.0	.0035
353.0	.0035
354.0	.0035
432.0	.0025
433.0	.0035
434.0	.0035
435.0	.0040
436.0	.0060
437.0	.0055
438.0	.0055
439.0	.0050
440.0	.0045
441.0	.0055
442.0	.0070
443.0	.0040
444.0	.0050
445.0	.0055
446.0	.0050
447.0	.0050
448.0	.0055
449.0	.0045
450.0	.0035
780.0	.0025
781.0	.0030
782.0	.0030
783.0	.0030
784.0	.0040
785.0	.0035
786.0	.0045
787.0	.0055
788.0	.0050
789.0	.0065
790.0	.0070
791.0	.0055
792.0	.0075
793.0	.0065
794.0	.0040
795.0	.0060
796.0	.0055
797.0	.0060
798.0	.0080
799.0	.0055
800.0	.0045
801.0	.0055
802.0	.0040
803.0	.0045
804.0	.0035
805.0	.0025
806.0	.0040
807.0	.0035
808.0	.0025
809.0	.0030
810.0	.0030
880.0	.0040
881.0	.0035
882.0	.0035
883.0	.0035
884.0	.0040
885.0	.0050
886.0	.0045
887.0	.0050
888.0	.0070
889.0	.0070
890.0	.0060
891.0	.0055
892.0	.0060
893.0	.0070
894.0	.0060
895.0	.0055
896.0	.0070
897.0	.0065
898.0	.0060
899.0	.0055
900.0	.0055
901.0	.0075
902.0	.0065
903.0	.0050
904.0	.0055
905.0	.0035
906.0	.0015
907.0	.0030

** 1ST RUN WITH PLUME DATA **

** DIODE vs. VOLTAGE **

210.0	.0035
211.0	.0027
212.0	.0033
213.0	.0040
214.0	.0043
215.0	.0050
216.0	.0045
217.0	.0018
218.0	.0048
219.0	.0043
220.0	.0048
221.0	.0050
222.0	.0045
223.0	.0040
224.0	.0050
225.0	.0048
226.0	.0035
227.0	.0040
228.0	.0038
229.0	.0045
230.0	.0048
231.0	.0038
232.0	.0038
233.0	.0025
234.0	.0025
235.0	.0027
236.0	.0025
237.0	.0048
238.0	.0043
239.0	.0050
240.0	.0052
241.0	.0050
242.0	.0040
243.0	.0037
244.0	.0043
245.0	.0030
246.0	.0052
247.0	.0040
248.0	.0045
249.0	.0030
250.0	.0035
251.0	.0043
252.0	.0018
253.0	.0033
254.0	.0045
430.0	.0027
431.0	.0025
132.0	.0027
433.0	.0033
434.0	.0040
435.0	.0043
436.0	.0050
437.0	.0050
438.0	.0053
439.0	.0047
440.0	.0050
441.0	.0048
142.0	.0047
443.0	.0050
444.0	.0050
445.0	.0050
446.0	.0045
447.0	.0043
448.0	.0038
449.0	.0038
450.0	.0033
780.0	.0033
781.0	.0033
782.0	.0040
783.0	.0033
784.0	.0040
785.0	.0042
786.0	.0050
787.0	.0060
788.0	.0065
789.0	.0060
790.0	.0060
791.0	.0063
792.0	.0060
793.0	.0052
794.0	.0067
795.0	.0060
796.0	.0060
797.0	.0065
798.0	.0055
799.0	.0060
800.0	.0052
801.0	.0050
802.0	.0017
803.0	.0038
804.0	.0033
805.0	.0027
806.0	.0030
807.0	.0028
808.0	.0030
809.0	.0033
810.0	.0027
890.0	.0027
891.0	.0019
892.0	.0027
893.0	.0037
894.0	.0047
895.0	.0050
896.0	.0018
897.0	.0047
898.0	.0043
899.0	.0040
870.0	.0060
891.0	.0065
892.0	.0070
873.0	.0065
874.0	.0063
895.0	.0063
876.0	.0050
897.0	.0063
878.0	.0067
899.0	.0057
900.0	.0063
901.0	.0060
902.0	.0038
903.0	.0043
904.0	.0033
905.0	.0023
906.0	.0030
907.0	.0033
908.0	.0035
909.0	.0047
910.0	.0027

** 2ND RUN W/O PLUME DATA **

** DIODE vs. VOLTAGE **

210.0	.0030
211.0	.0027
212.0	.0033
213.0	.0037
214.0	.0033
215.0	.0037
216.0	.0033
217.0	.0043
218.0	.0043
219.0	.0053
220.0	.0046
221.0	.0050
222.0	.0053
223.0	.0053
224.0	.0047
225.0	.0040
226.0	.0047
227.0	.0050
228.0	.0043
229.0	.0043
230.0	.0033
231.0	.0033
232.0	.0030
233.0	.0037
235.0	.0033
236.0	.0047
237.0	.0027
238.0	.0037
239.0	.0030
240.0	.0030
241.0	.0043
242.0	.0040
243.0	.0043
244.0	.0047
245.0	.0053
246.0	.0047
247.0	.0040
248.0	.0047
249.0	.0037
250.0	.0037
251.0	.0043
252.0	.0030
253.0	.0027
254.0	.0037
430.0	.0023
431.0	.0047
432.0	.0027
433.0	.0033
434.0	.0040
435.0	.0033
436.0	.0047
437.0	.0037
438.0	.0043
439.0	.0050
440.0	.0050
441.0	.0060
442.0	.0057
443.0	.0063
444.0	.0053
445.0	.0057
446.0	.0053
447.0	.0047
448.0	.0047
449.0	.0027
450.0	.0033
730.0	.0033
781.0	.0027
782.0	.0030
783.0	.0033
784.0	.0027
785.0	.0037
786.0	.0033
787.0	.0053
788.0	.0050
789.0	.0060
790.0	.0060
791.0	.0067
792.0	.0073
793.0	.0060
794.0	.0063
795.0	.0070
796.0	.0067
797.0	.0063
798.0	.0053
799.0	.0067
800.0	.0057
801.0	.0050
802.0	.0050
803.0	.0043
804.0	.0043
805.0	.0033
806.0	.0043
807.0	.0030
808.0	.0033
809.0	.0023
810.0	.0037
880.0	.0030
881.0	.0030
882.0	.0027
883.0	.0027
884.0	.0027
885.0	.0027
886.0	.0027
887.0	.0047
888.0	.0037
889.0	.0047
890.0	.0060
891.0	.0060
892.0	.0087
893.0	.0057
894.0	.0067
895.0	.0070
896.0	.0067
897.0	.0060
898.0	.0043
899.0	.0050
900.0	.0040
901.0	.0047
902.0	.0023
903.0	.0037
904.0	.0043
905.0	.0027
906.0	.0040
907.0	.0027
908.0	.0037
909.0	.0027
910.0	.0030

** 2ND RUN WITH PLUME DATA **

** DIODE vs. VOLTAGE **

210.0	.0028
211.0	.0035
212.0	.0038
213.0	.0042
214.0	.0035
215.0	.0043
216.0	.0043
217.0	.0045
218.0	.0050
219.0	.0045
220.0	.0045
221.0	.0045
222.0	.0033
223.0	.0045
224.0	.0035
225.0	.0035
226.0	.0048
227.0	.0040
228.0	.0040
229.0	.0030
230.0	.0030
231.0	.0035
232.0	.0030
233.0	.0033
335.0	.0027
336.0	.0040
337.0	.0030
338.0	.0035
339.0	.0030
340.0	.0035
341.0	.0033
342.0	.0038
343.0	.0035
344.0	.0025
345.0	.0018
346.0	.0043
347.0	.0038
348.0	.0043
349.0	.0033
350.0	.0033
351.0	.0027
352.0	.0030
353.0	.0025
354.0	.0025
430.0	.0025
431.0	.0025
432.0	.0025
433.0	.0033
434.0	.0040
435.0	.0035
436.0	.0040
437.0	.0040
438.0	.0050
439.0	.0050
440.0	.0045
441.0	.0053
442.0	.0053
443.0	.0058
444.0	.0043
445.0	.0040
446.0	.0045
447.0	.0030
448.0	.0033
449.0	.0040
450.0	.0033
781.0	.0033
781.0	.0028
782.0	.0075
783.0	.0025
784.0	.0035
785.0	.0042
786.0	.0038
787.0	.0042
788.0	.0013
789.0	.0060
790.0	.0065
791.0	.0055
792.0	.0050
793.0	.0055
794.0	.0072
795.0	.0055
796.0	.0050
797.0	.0063
798.0	.0060
799.0	.0057
800.0	.0038
801.0	.0045
802.0	.0045
803.0	.0040
804.0	.0033
805.0	.0030
806.0	.0035
807.0	.0025
808.0	.0033
809.0	.0015
810.0	.0027
880.0	.0027
881.0	.0023
882.0	.0025
883.0	.0020
884.0	.0123
885.0	.0030
886.0	.0033
887.0	.0040
888.0	.0043
889.0	.0050
890.0	.0057
891.0	.0018
892.0	.0050
893.0	.0055
894.0	.0060
895.0	.0057
896.0	.0047
897.0	.0053
898.0	.0055
899.0	.0045
900.0	.0039
901.0	.0043
902.0	.0043
903.0	.0033
904.0	.0033
905.0	.0025
906.0	.0023
907.0	.0020
908.0	.0035
909.0	.0023
910.0	.0015

** 3RD RUN W/O PLUME DATA **

** DIODE vs. VOLTAGE **

210.0	.0040
211.0	.0040
212.0	.0050
213.0	.0055
214.0	.0050
215.0	.0050
216.0	.0055
217.0	.0055
218.0	.0065
219.0	.0050
220.0	.0070
221.0	.0055
222.0	.0070
223.0	.0045
224.0	.0060
225.0	.0035
226.0	.0060
227.0	.0040
228.0	.0060
229.0	.0035
230.0	.0045
231.0	.0035
232.0	.0050
233.0	.0040
234.0	.0035
235.0	.0040
236.0	.0035
237.0	.0040
238.0	.0045
239.0	.0050
240.0	.0045
241.0	.0050
242.0	.0050
243.0	.0045
244.0	.0040
245.0	.0030
246.0	.0030
247.0	.0035
248.0	.0040
249.0	.0040
250.0	.0030
251.0	.0040
252.0	.0035
253.0	.0030
254.0	.0030
430.0	.0040
431.0	.0035
432.0	.0035
433.0	.0050
434.0	.0055
435.0	.0050
436.0	.0065
437.0	.0050
438.0	.0065
439.0	.0055
440.0	.0065
441.0	.0050
442.0	.0065
443.0	.0050
444.0	.0055
445.0	.0040
446.0	.0045
447.0	.0035
448.0	.0045
449.0	.0035
450.0	.0050
780.0	.0035
781.0	.0035
782.0	.0030
783.0	.0040
784.0	.0050
785.0	.0055
786.0	.0065
787.0	.0060
788.0	.0065
789.0	.0065
790.0	.0065
791.0	.0075
792.0	.0065
793.0	.0070
794.0	.0055
795.0	.0070
796.0	.0060
797.0	.0065
798.0	.0050
799.0	.0050
800.0	.0030
801.0	.0030
802.0	.0025
803.0	.0030
804.0	.0030
805.0	.0040
806.0	.0025
807.0	.0040
808.0	.0030
809.0	.0040
810.0	.0025
880.0	.0025
881.0	.0025
882.0	.0025
883.0	.0035
884.0	.0035
885.0	.0050
886.0	.0050
887.0	.0070
888.0	.0055
889.0	.0065
890.0	.0060
891.0	.0060
892.0	.0060
893.0	.0060
894.0	.0060
895.0	.0060
896.0	.0055
897.0	.0045
898.0	.0050
899.0	.0045
900.0	.0025
901.0	.0030
902.0	.0030
903.0	.0035
904.0	.0025
905.0	.0030
906.0	.0030
907.0	.0030
908.0	.0035
909.0	.0030
910.0	.0030

** 3RD RUN WITH PLUME DATA **

** DIODE vs. VOLTAGE **

210.0	.0023
211.0	.0023
212.0	.0033
213.0	.0037
214.0	.0023
215.0	.0030
216.0	.0037
217.0	.0043
218.0	.0053
219.0	.0043
220.0	.0010
221.0	.0050
222.0	.0050
223.0	.0043
224.0	.0040
225.0	.0040
226.0	.0053
227.0	.0047
228.0	.0047
229.0	.0027
230.0	.0030
231.0	.0030
232.0	.0050
233.0	.0033
335.0	.0030
336.0	.0033
337.0	.0030
338.0	.0037
339.0	.0030
340.0	.0037
341.0	.0040
342.0	.0047
343.0	.0033
344.0	.0043
345.0	.0037
346.0	.0040
347.0	.0050
348.0	.0040
349.0	.0033
350.0	.0030
351.0	.0033
352.0	.0030
353.0	.0037
354.0	.0037
430.0	.0033
431.0	.0030
432.0	.0033
433.0	.0033
434.0	.0037
435.0	.0030
436.0	.0030
437.0	.0037
438.0	.0047
439.0	.0053
440.0	.0047
441.0	.0050
442.0	.0057
443.0	.0047
444.0	.0043
445.0	.0037
446.0	.0043
447.0	.0040
448.0	.0037
449.0	.0033
450.0	.0030
780.0	.0030
781.0	.0027
782.0	.0030
783.0	.0030
784.0	.0037
785.0	.0040
786.0	.0047
787.0	.0040
788.0	.0037
789.0	.0053
790.0	.0060
791.0	.0063
792.0	.0060
793.0	.0060
794.0	.0050
795.0	.0067
796.0	.0057
797.0	.0057
798.0	.0060
799.0	.0053
800.0	.0050
801.0	.0047
802.0	.0043
803.0	.0043
804.0	.0037
805.0	.0030
806.0	.0030
807.0	.0027
808.0	.0027
809.0	.0030
810.0	.0027
880.0	.0027
881.0	.0030
882.0	.0027
883.0	.0027
884.0	.0033
885.0	.0040
886.0	.0037
887.0	.0033
888.0	.0040
889.0	.0040
890.0	.0043
891.0	.0060
892.0	.0057
893.0	.0060
894.0	.0057
895.0	.0063
896.0	.0063
897.0	.0057
898.0	.0057
899.0	.0057
900.0	.0050
901.0	.0047
902.0	.0043
903.0	.0047
904.0	.0033
905.0	.0030
906.0	.0030
907.0	.0030
908.0	.0033
909.0	.0027
910.0	.0030

B. DATA ACQUISITION PROGRAM

```
20   !********** ACQUIRES MULTIPLE SCANS OF BOTH DIODE ARRAYS **************
30   !**********          AND STORES THEM ON DISK              *** ***********
40   !**********      HANSEN,KELLY HARRIS,KIM HONG-ON 1991     **************
50    OPTION BASE 1
60    COM Q1$[12],Q2$[12],T1$[20],D1$[12],D2$[12],Address(4),E(4096)
70    COM A(1024) BUFFER,B(4096) BUFFER,C(4096) BUFFER,D(4096) BUFFER
80    ASSIGN @Multi10 TO 72310                    !CLEARS THE WAKE-UP SERVICE REQUEST
90    ENTER @Multi10;Qq1,Qq2,Qq3,Qq4,Qq5,Qq6                !OF THE MULTIPROGRAMMER
100   MAT Address= (0)                            !ZEROS THE ARRAY FOR DEBUGGING
120   LOCAL LOCKOUT 7        ! DISABLES FRONT PANELS OF DATA ACQUISITION SYSTEM
130   REMOTE 709
140   OUTPUT 709;"AR"                             ! ANALOG RESET OPENS ALL CHANNELS
160   REMOTE 722                                  !REMOTE IS A LISTEN COMMAND
170   OUTPUT 722;"HSM002SO1D1L1Z0F1FL0R1ISTN.01STI13Q"        !PROGRAM VOLTMETER
180   ! H homes the DVM .(like RESET)  SM002 sets the service request mask to
190   ! tell the computer that a measurement was taken and is ready to be read.
200   ! page 3-30 of DVM MANUAL. SO1 means that no reading will be taken until
210   ! the computer receives the one just made(page 3-26). D1 means DISPLAY ON.
220   ! L1 means load the following instructions. Z0 means AUTO ZERO OFF for
230   ! faster but less precise readings. F1 means DC VOLTS measurement.
240   ! FL0 means FILTER OFF for faster readings. R1 is AUTO RANGING. 1STN means
250   ! 1 reading will be taken for each trigger. .01STI---.01powerline cycles
260   ! will be the integration time. T3 is a single trigger. Q means END
270   PRINT USING "3/"
280   PRINT "ENTER THE FILENAMES OF THE DATA FILES TO BE CREATED (e.g. RAW1,RAW2)"
290   PRINT "                                  12 CHARACTERS MAXIMUM, EACH"
300   PRINT USING "/"
310   PRINT "           AN  EMPTY  DISK  MUST  BE  IN  THE  LEFT  DISK  DRIVE "
320   PRINT ""
330   PRINT "                    THE DATA FILES WILL NEARLY FILL A DISK"
340   PRINT USING "/"
350   MASS STORAGE IS ":CS80,700"          ! CHANGE THIS LATER IF NECESSARY
360   INPUT "            INPUT FILE NAMES NOW - (FILENAME1,FILENAME2) ",D1$,D2$
370   MS=1024
380   Zz$=":INTERNAL,4,1"                        ! STRING INDICATES MASS STORAGE
390   CREATE BDAT D1$&Zz$,6144,16    ! 12 SCANS OF 1024  @ 2*8 BYTES PER RECORD
400   CREATE BDAT D2$&Zz$,6144,16    ! 1024*12/2=NUMBER OF RECORDS=6144)
410   PRINT USING "@"
420   PRINT "       DATA WILL BE STORED ON DISKETTE WITH FOLLOWING FILE NAMES:"
430   PRINT USING "///"
440   PRINT "                       NO PARTICLES ---- FILENAME = ";D1$
450   PRINT "                       PARTICLES ------- FILENAME = ";D2$
451   OUTPUT 707;"DC11,2"    ! OPEN SHUTTER
460   PRINT USING "//"
470   PRINT "                IS THIS A CALIBRATION ?   ENTER   Y  IF YES "
480   PRINT "                       ANYTHING  ELSE  IF  ACTUAL  RUN"
490   INPUT R$
500   PRINT USING "//"
510   PRINT "                           BE SURE LASER IS ON"
520   PRINT "                     PRESS (CONTINUE) WHEN READY"
530   PAUSE
540   IF R$="Y" THEN 740
550   PRINT USING "@"
560   INPUT "ENTER THE THE TRIGGER VOLTAGE",Vt
590   OUTPUT 709;"AC20"                          !CHANNEL FOR CHAMBER PRESSURE
600   WAIT .3                          ! THIS WAIT IS TO LET VOLTAGES SETTLE DOWN
610   V1=0
620   CLEAR 722          ! THIS DOES NOT ALTER THE INSTRUCTIONS FOR THE VOLTMETER
630                     !IT CLEARS ANY NUMBERS IN THE DISPLAY OR OUTPUT REGISTERS
640   FOR I=1 TO 10
650   OUTPUT 722;"X1"                            !TRIGGER VOLTMETER
660   GOSUB Reading                              !READ VOLTMETER
```

```
670   V1=V1+V
680   NEXT I
690   Vz=V1/10              ! THIS AVERAGES READINGS TO GET A ZERO PRESSURE VALUE
700   PRINT USING " 40A,D.6D";"              ZERO PRESSURE VOLTAGE IS       ";Vz
710   PRINT "
731   PRINT "   DATA ACQUISITION BEGINS WHEN VOLTAGE EXCEEDS    ";Vt
740   D2$=D1$                                ! NO-PARTICLES STRING NAME
750   GOSUB Multiprog                        ! TAKES NO-PARTICLE DATA
760   GOSUB Storedata
770   IF R$="Y" THEN 960                     ! IF CALIBRATION THEN SKIP SOME LINES
780   PRINT USING "/"
790   PRINT "                              BE SURE NITROGEN IS ON"
800   PRINT "BE SURE VISICORDER IS SET UP TO RUN ON PROPER SCALE WITH LAMP ON."
810   PRINT USING "/"
820   DISP "                               STANDING BY FOR IGNITION"
830   PRINT "                              STANDING BY FOR IGNITION"
840   BEEP 2000,.1
850   OUTPUT 709;"AC20"                          ! CONNECT PRESSURE XDUCER TO DVM
860   CLEAR 722
870   WAIT .3
880   OUTPUT 722;"X1"                            ! TRIGGER VOLTMETER
890   GOSUB Reading
900   R9=ABS(V-Vz)                    !THIS IS VOLTAGE CORRESPONDING TO PRESSURE
910   PRINT R9
920   IF R9<Vt THEN GOTO 880 !   IF PRESSURE IS BELOW THRESHOLD PRESSURE--REPEAT
921   DISP ""
930   O0=TIMEDATE
940   WAIT T8-.13              ! ALLOWS FOR .13 SECONDS TO PROGRAM MEMORY CARDS
950   IF R$<>"Y" THEN 1020                    !IF ACTUAL RUN THEN SKIP SOME LINES
960   !                  FOR CALIBRATIONS INTRODUCE PARTICLES AND THEN CONTINUE
970   PRINT CHR$(12)
980   PRINT USING "//////"
990   PRINT "                INTRODUCE PARTICLES THEN PRESS KEY # 9 TO TAKE DATA"
1000  ON KEY 9 LABEL "  TAKE DATA" GOTO 1020
1010  Standby: GOTO Standby
1020  GOSUB Multiprog                                      ! TAKE PARTICLE DATA
1040  D2$=D2$                                          !PARTICLE DATA FILE NAME
1050  GOSUB Storedata
1060  PRINT "ELAPSED TIME FROM PRESSURE TO END OF TIME DELAY";DROUND(O1-O0,3)
1070  PRINT "ELAPSED TIME FROM START TO END OF DATA ACQUISITION";DROUND(O2-O1,3)
1080  PRINT "          DATA STORED ON DISK WITH FILENAMES (";D1$;") AND (";D2$;")"
1081  OUTPUT 709;"AR"
1082  LOCAL 7
1090  GOTO End
1100  Multiprog: !
1101  OUTPUT 709;"DC10,6"
1102  OUTPUT 709;"DD10,3"
1110  OUTPUT 723;"CC,2,3,12,13T"
1120  OUTPUT 723;"CC,5,6,7,10T"  !CLEARS THE ARM,BUSY AND EOP OF MEMORY CARDS
1130  OUTPUT 723;"CC,1,4,11T"    !CLEARS SAME FOR A TO D'S AND TIMER PACER
1140  OUTPUT 723;"SF,2,3,1,.001,12,T"      ! THE (1) IS 2'S COMPLIMENT BINARY
1150  OUTPUT 723;"SF,5,3,1,.001,12,T"   ! THE .001 IS THE LEAST SIGNIFICANT BIT
1160  OUTPUT 723;"SF,9,3,1,.001,12,T"   ! THE 12 IS FOR 12 BIT WORD SIZE
1170  OUTPUT 723;"SF,12,3,1,.001,12,T"  ! SINCE THE A TO D IS 12 BIT
1180  OUTPUT 723;"WF,3,1023T,WF,8,4095T"
1190  OUTPUT 723;"WF,10,4095T,WF,13,4095T"
1200  !  SETS REFERENCE WORD FOR WHEN TO STOP TAKING DATA AND GENERATE INTERRUPT
1210  OUTPUT 723;"WF,2.1,21T,WF,5.1,21T"      !SETS FIFO MODE
1211  OUTPUT 723;"WF,9.1,1T,WF,12.1,1T"
1220  OUTPUT 723;"WF,3.1,0T,WF,3.2,0T,WF,3.3,0T,WF,13.1,0T,WF,13.2,0T,WF,13.3,0T"
1230  OUTPUT 723;"WF,6.1,0T,WF,6.2,0T,WF,6.3,0T,WF,10.1,0T,WF,10.2,0T,WF,10.3,0T"
1240            ! SETS COUNTER AND POINTERS OF 2ND MEMORY CARD IN EACH PAIR TO 0
1250  OUTPUT 723;"AC,2T,AC,5T,AC,9T,AC,12T"!ARMS CARDS WHICH GENERATE INTERRUPT
1260  OUTPUT 723;"AC,3T,AC,6T,AC,10T,AC,13T"
1270  O1=TIMEDATE
1280  OUTPUT 723;"WF,4.2,0T,WF,4,2ST"  ! TIMER PACER GIVES 1 PULSE OF 1 SEC WHEN
1290            ! TRIGGERED  BY THE BLANKING PULSE (PLENTY OF TIME FOR 8 SCANS)
```

```
1291  WAIT .8
1300          !MAY NOT NEED ANY WAIT LONGER THAN .5 SECONDS FOR ALL CARDS TO FILL
1310  OUTPUT 723;"WF,2.1,1T WF,5.1,1T"      !ENABLE THE MEMORY CARD
1320  OUTPUT 709;"DC10,3"
1330  OUTPUT 709;"DC11,2"
1340  OUTPUT 709;"DC10,6"
1350  WAIT 2 !
1360  K=SPOLL(723)                                    !WAIT FOR MEM INTERRUPT
1370  IF K<>64 THEN GOTO 1310
1380  OUTPUT 723;"WF,4.2,1T"    ! MAY BE UNNECESSARY TO ALTER TIMER  PACER SINCE
1390  !          MEMORY CARDS HAVE AUTOMATIC LOCKOUT BUT FOR NOW WE WILL DO IT
1400  D2=TIMEDATE
1410  OUTPUT 709;"DC11,2"
1420  ON ERROR GOTO Err_trap          ! NEEDED TO READ ARMED CARD INTERRUPT LIST
1430  SEND 7;UNL MLA TALK 23 SEC 12   ! SPECIFICALLY ASKS FOR INTERRUPT LIST
1440 Var_read:   ENTER 7;Address(x)              !READ WHICH CARDS INTERRUPTED
1450 MemCards:  PRINT "            MEMORY CARDS WHICH GENERATED INTERRUPTS ARE "
1460  PRINT "                        SLOTS# = ",Address(x)
1470  MAT Address= (0)
1480  OFF ERROR
1490  OUTPUT 723;"DC,3,6,13,10T"                          !DISSARM MEM CARDS
1500  OUTPUT 723;"MI,2,1024T"                       ! SET UP CARD TO BE READ
1510  ENTER 72305;A(X)                      ! GETS DATA FROM 1024 MEMORY BOARD
1520  OUTPUT 723;"MI,5,4096T"
1530  ENTER 72305,B(X)                      ! GETS DATA FROM 4096 MEMORY BOARD
1540  PRINT "                    EXHAUST   DATA ENTERED"
1550  OUTPUT 723;"MI,12,4096T"
1560  ENTER 72305,C(X)
1570  OUTPUT 723;"MI,9,4096T"
1580  ENTER 72305;D(X)
1590  ENABLE INTR 7;8
1600  PRINT "                    MOTOR     DATA ENTERED"
1610  MAT A= (-1)*A         ! THE 1024 CARD IS INCLUDED BUT NOT SAVED. IT DIDN'T
1620  MAT B= (-1)*B         ! PERFORM WELL. COULD BE REPLACED BY A 4096 CARD.
1630  MAT C= (-1)*C
1640  MAT D= (-1)*D         ! DIODE VOLTAGES ARE NEGATIVE SO SIGNS ARE CHANGED
1650  RETURN
1660 Store_data:!
1670  ASSIGN @Diskfile TO D$&Z$
1680  ASSIGN @Buff1 TO BUFFER C(X)                  ! MOTOR CAVITY 4 SCANS
1690  ASSIGN @Buff2 TO BUFFER D(X)                  ! MOTOR CAVITY 4 SCANS
1700  ASSIGN @Buff3 TO BUFFER B(X)                  ! EXHAUST      4 SCANS
1710  CONTROL 6Buff1,3;1,32768,1              !SETS BUFFER POINTERS TO FULL
1720  CONTROL 6Buff2,3;1,32767,1             !INTERFACE REGISTERS SECTION OF
1730  CONTROL 6Buff3,3;1,32767,1                        !LANGUAGE MANUAL
1740  TRANSFER @Buff1 TO @Diskfile           ! ORDER OF DATA ON THE DISK IS
1750  WAIT FOR EOT @Diskfile                        ! MOTOR CAVITY--8 SCANS
1760  TRANSFER @Buff2 TO @Diskfile                  ! EXHAUST   -- 4 SCANS
1770  WAIT FOR EOT @Diskfile                       !WAIT BECAUSE OVERLAPPING
1780  TRANSFER @Buff3 TO @Diskfile                 !TRANSFERS ARE NOT WANTED
1790  WAIT FOR EOT @Diskfile
1800  ASSIGN @Diskfile TO *                             !CLOSE I / O PATHS
1810  ASSIGN @Buff1 TO *
1820  ASSIGN @Buff2 TO *
1830  ASSIGN @Buff3 TO *
1840  RETURN
1850 Read_hg:!
1860  ENTER 722;V                           !READS VOLTMETER
1870  RETURN
1880 Err_trap:  IF ERRN=159 AND ERRL(Var_read) THEN MemCards
1890  PRINTER ERRNS                        !EVEN IF THE ERROR WAS NOT THE ONE PLANNED
1900  GOTO MemCards                        !FOR PROGRAM EXECUTION CONTINUES
1910  OUTPUT 709;"DC10,15" ! THIS ACTIVATES THE MALVERN EXT TRIGGER (VOLTS = 5)
1920  PRINT "TAKING DATA WITH MALVERN"
1930  WAIT 3
1940  PRINT "RESETTING MALVERN"
1950  OUTPUT 709;"DC10,15"
1960  PRINT "  RUN COMPLETED WITH MALVERN ONLY DATA"
1970 End: END
```

REFERENCES

1. Netzer, D. W., *Tactical Missile Propulsion-Design and Applications*, Unpublished Course Notes, Naval Postgraduate School, 1991.

2. Dash, S. M., *Analysis of Exhaust Plumes and Their Interaction with Missile Airframes*, A.I.A.A. Progress in Astronautics and Aeronautics, Vol. 104, Tactical Missile Aerodynamics, pp. 778-851.

3. Hwang, C. J. and Chang, G. C., *Numerical Study of Gas-Particle Flow in Solid Rocket Nozzle*, AIAA J., Vol. 26, No. 6, June 1988, pp. 682-689.

4. Lyons, R. B., Wormhoudt, J. and Gruninger, J., *Scattering of Radiation by Particles in Low Altitude Plumes*, AIAA-81-1053, AIAA 16th Thermophysics Conference, June 1981, Palo Alto, CA.

5. Cashdollar, K. L., Lee, C. K. and Singer, J. M., *Three-Wavelength Ligh Transmission Technique to Measure Smoke Particle Size and Concentration*, Applied Optics, Vol. 18, No. 11, June 1979, pp. 1763-1769.

6. Mie A. F. W. L, Gustav,*Contributions to the Optics of Cloudy Media, Especilly of Colloidal Metalic Solutions*, Ann. Physik 4th sreies, 25:3:377-445, 1908.

7. Dobbins, R. A., and Jizmagian, J., *Particle Measurements Based on Use of Mean Scattering Cross-section,* Opt. Soc. Am., Vol. 56, No. 10, pp 1351-1354, 1966.

8. Rosa, J. S., *Particle Sizing in a Solid Propellant Rocket Motor Using Scattered Light Mearsurements*, Master's Thesis, Naval Postgraduate School, Monterey, California, December 1985.

9. Oriel Corp., *Light Sources*, Oriel Catalog, Volume II, Strafford, CT.

10. EG & G Reticon, *Spectral Response of Reticon Linear Photodiode Arrays*, Application Notes, No.121, Sunnyvale, California.

11. Harris, R. K., *An Apparatus for Sizing Particulate Matter in Solid Rocket Motors*, Master's Thesis, Naval Postgraduate School, Monterey, California, June 1984.

12. Lotus Corp., *Lotus123, Release 3.1*, pp 2-70 - 2-74, Cambridge, Massachusetts.

13. Spiegel, M. R., *Probability and Statistics*, McGraw Hill, pp 263-265, 1990.

INITIAL DISTRIBUTION LIST

		NO. Copies
1.	Defence Technical Information Center Cameron Station Arlington, Virginia 22304-6145	2
2.	Library, Code 52 Naval Postgraduate School Monterey, California 93943-5002	2
3.	Department Chairman, Code AA Department of Aeronautics Naval Postgraduate School Monterey, California 93943-5000	1
4.	Professor D. W. Netzer, Code AA/Nt Department of Aeronautics Naval Postgraduate School Monterey, California 93943-5000	2
5.	David Laredo, Code AA Department of Aeronautics Naval Postgraduate School Monterey, California 93943-5000	1
6.	Major Kim, Hong-on 839-4 Bokdae-Dong Cheongju-Shi Seoul Korea 360-270	5

Thesis
K41457 Kim
c.1 Multiple-wavelength
transmission measurements
in rocket motor plumes.

Thesis
K41457 Kim
c.1 Multiple-wavelength
transmission measurements
in rocket motor plumes.

DUDLEY KNOX LIBRARY
3 2768 00037055 5